G.E.C. Journal

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CONTENTS

PAGE

FRONTISPIECE: POURING A CHARGE FROM A WITTON HIGH FREQUENCY ELECTRIC MELTING FURNACE AT THE WORKS OF JONAS & COLVER (NOVO), LTD., SHEFFIELD – – 82

HIGH FREQUENCY ELECTRIC MELTING FURNACE EQUIPMENT 83
By Engineers of The General Electric Co., Ltd.

MAGNETRON VALVES FOR ULTRA-SHORT WAVELENGTHS – 94
By E. C. S. Megaw.

THE TESTING OF LARGE ALTERNATING CURRENT CIRCUIT BREAKERS.
PART II.—GENERAL DESCRIPTION OF THE HIGH POWER TEST LABORATORY AT WITTON – – – – 108
By. W. Wilson.

PART III.—THE ALTERNATOR AND ITS AUXILIARY EQUIPMENT – – – – – – – – 115
By M. Kahn.

A NEW LEAD EXTRUDING MACHINE – – – – 120
By R. E. Horley.

TURBO-BLOWERS AND TURBO-COMPRESSORS—PART III. – 127
By. B. Pochobradsky.

ELECTRIC ARC WELDING – – – – – – 134
By E. C. Davis.

VOLTAGE REGULATION OF A.C. TRANSMISSION AND DISTRIBUTION SYSTEMS.
PART II.—DESIGN OF REGULATING APPARATUS – – 147
By C. H. Nunn.

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Pouring a charge from a Witton high frequency electric melting furnace at the works of Jonas & Colver (Novo) Ltd., Sheffield. (*see page 83*). **This illustration is reproduced from a photograph taken by the light of the molten metal.**

G.E.C. Journal

VOL. VII. MAY, 1936. No. 2.

High Frequency Electric Melting Furnace Equipment.

(STOBIE PATENTS)

AN INSTALLATION AT THE WORKS OF JONAS & COLVER (NOVO) LTD. SHEFFIELD.

By Engineers of The General Electric Co., Ltd.

THE firm of Jonas and Colver (Novo), Ltd., was founded in Sheffield during the year 1870 when steel making operations were first begun in the Novo Steel Works. It is interesting to note that in the earliest days the whole of the steel produced was made from wrought iron by the cementation process followed by forging. There was only one process of steel melting, namely the crucible process which is still used for the production of some special steels, but other processes for melting have since been developed, culminating in the introduction of electric furnaces. Throughout its history the firm has consistently installed the most modern types of equipment not only for melting purposes, but also for further processes in steel manufacture. Thus a comprehensive forging installation has been laid down; also there are adequate rolling mills for rolling hot and cold rolled bars, strip and sheets, etc. In addition, a complete heat treatment plant affords facilities for the production of aircraft, automobile and other grades of high class steels. The firm also makes the well known brands of high speed steel marketed under the name "Novo."

One of the most recent additions to the equipment of the works is a Witton high frequency melting installation, comprising two furnaces together with the necessary electric converting plant, condensers, switch and control gear, etc. The capacity of one furnace is ½-ton and that of the other 100 lbs. The whole of this plant was manufactured by The General Electric Co., Ltd.

ADVANTAGES OF HIGH FREQUENCY MELTING.

The development and practical application of the high frequency furnace has probably had a more pronounced influence on steel works practice than any other individual innovation during the last twenty or thirty years. There has been a rapid growth both in the capacity of the unit and also in the number of equipments which have been installed during the last year or two. These advances afford an indication of the important economic and metallurgical advantages which are peculiar to this type of furnace. Its chief application has been to the production of high grade carbon and alloy tool steels and other complex alloys such as stainless and heat resisting steels, mainly from clean material of known composition. The conditions pertaining to their manufacture in the casting shop are virtually those associated with laboratory methods so far as precision, control, and cleanliness are concerned.

The steel made in the high frequency furnace on a commercial basis is found to be of exceptional purity and uniformity of analysis. Stainless and other steels which contain high percentages of chromium, tungsten, molybdenum and other alloying

additions are made without appreciable loss of these constituents and without carbon increment or the picking up of sulphur or other deleterious elements.

So far as uniformity of product is concerned, it has been proved that if more than one ingot is poured from one melt, each ingot and every part of each ingot gives practically the same analysis. This

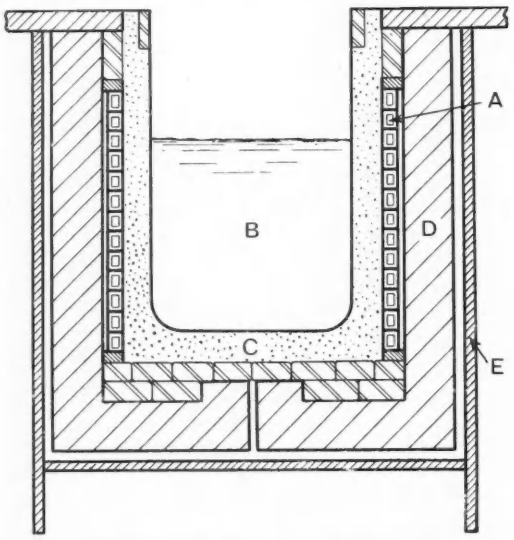


Fig. 1.—Diagram of Witton high frequency electric melting furnace (Stobie patents).

is due to the well known stirring effect within the molten charge which is inherent and peculiar to the high frequency furnace.

Another interesting feature of this type of furnace is the small mass and weight of the refractory lining. This enables the furnace to be used

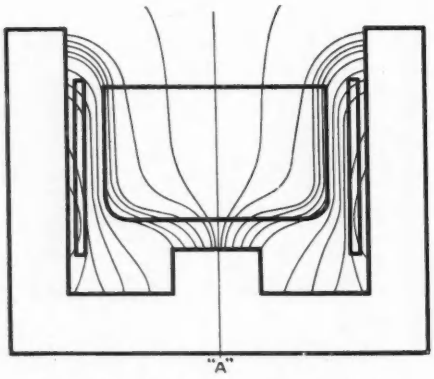


Fig. 2.—Flux distribution in Witton high frequency furnace with charge molten.

intermittently without appreciable increase in current consumption. It also enables alternative furnaces to be worked off the one plant with reasonable economy, thereby increasing the flexibility of the plant and adding appreciably to its general adaptability and usefulness. This feature also renders the pouring temperature of the steel susceptible to more precise control than is possible with other types of furnaces. When it is desired to superheat the charge prior to pouring, this can be achieved in a few minutes.

Working conditions are greatly improved, as may be judged from various of the illustrations. They are clean, and so far as the workmen are concerned, comparatively cool and comfortable. In this connection it may be pointed out that in the high frequency electric melting furnace there is no temperature gradient between the source of heat and the charge; the heat is actually generated within the charge itself, which is hotter than the crucible or furnace containing it.

The advantages enumerated are obtained without any corresponding increase in working costs. In general the current consumption per unit of output is low in comparison with the arc type of furnace and the cost of electrical energy usually compares favourably with the fuel costs of other types of furnaces. The cost of electrodes, which is not inconsiderable with arc type furnaces, is eliminated. Labour costs are low and, owing to the long life of the refractory lining, maintenance costs per ton of steel produced compare very favourably with those associated with other types of furnaces.

PRINCIPLES OF THE HIGH FREQUENCY FURNACE.

The high frequency melting furnace has been described previously,[1] but for the purposes of this article it is proposed to restate briefly its general construction and the principles upon

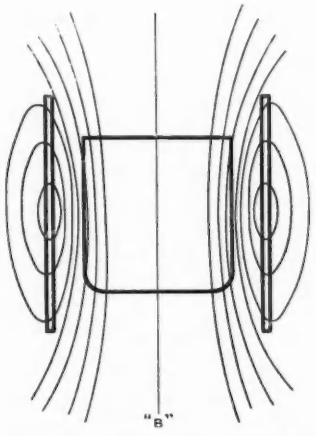


Fig. 3.—Comparative flux distribution of coreless type furnace with charge molten.

which it is designed, with particular reference to the Witton furnace which is based on Stobie patents. The fundamental parts of this type of high frequency furnace—shown diagrammatically at fig. 1—consist of (1) a spiral water cooled inductor coil A; (2) the

1. "G.E.C. Journal," Vol. III., Nos. 2 and 4, pp. 115, 205.

charge to be melted B; (3) the furnace lining C which serves as a crucible and heat insulator of the charge from the inductor; (4) an external laminated silicon steel core D consisting of four (or more) vertical external legs and bottom yokes with a foreshortened central core; and (5) a metal case E which supports the furnace as a whole and enables it to be tilted for pouring, etc.

If an alternating current is passed through the inductor coil A, a magnetic field is set up in a similar manner to an ordinary solenoid. This magnetic field will pass through the closed electrical circuits made by the pieces of metal which comprise the charge and will induce therein a voltage and consequently a current flow, which heats the charge during the preliminary stage. If the charge is magnetic, the reluctance of the magnetic path is initially low and increases as the charge becomes heated and non-magnetic.

Due to the skin effect in both the charge and the inductor coil caused by the high frequency of the supply, current can flow only on the surface of the charge and the inductor, the depth of penetration being only a few millimetres. Under molten conditions the magnetic lines through the charge are generally as shown in fig. 2. It will be seen that the flux produced by the inductor in effect interlinks with a thin cylinder of metal of comparatively high resistance, causing a current to flow round the cylinder, thus raising its temperature.

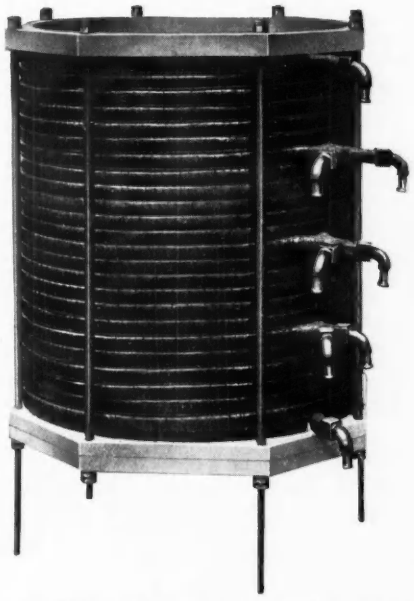


Fig. 4.—Inductor coil of Witton high frequency electric melting furnace (Stobie patents).

The Witton high frequency furnace incorporates the distinctive feature of the Stobie patent which covers the high permeability steel core external to the inductor, figs. 1 and 5. This core decreases the reluctance of the external magnetic circuit and thereby raises the inherent power factor. Further, this distinctive feature gives a high coupling factor between the inductor and the charge, particularly at the beginning of the melt, when the direction of the flux lines is controlled by the core. This is seen by comparing figs. 2 and 3. Again, when this special shroud is not used, shields have

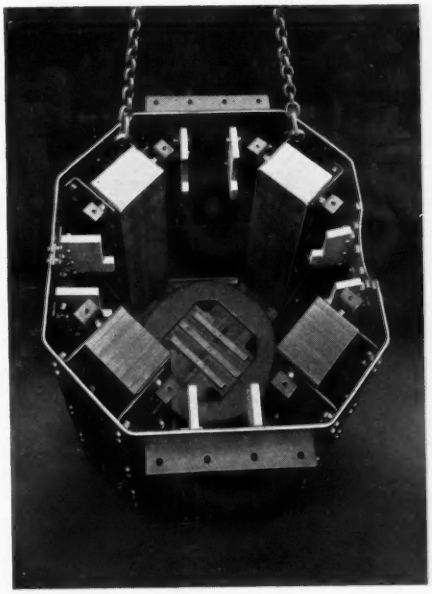


Fig. 5.—Interior of furnace with cores in position.

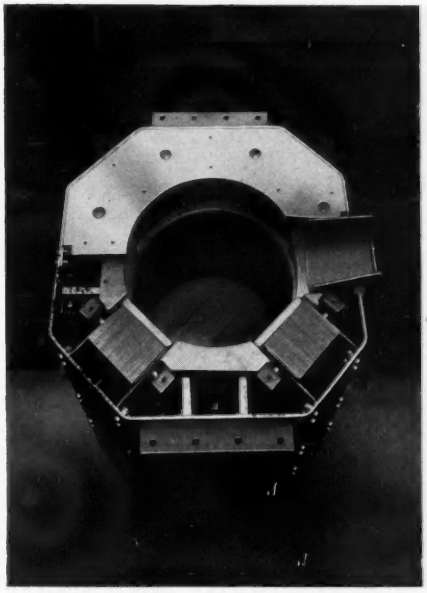


Fig. 6.—Interior of furnace with inductor coil in position.

Fig. 7.—General view of melting shop.

to be placed outside the inductor to prevent the external field from the conductor spreading and cutting local ironwork with resultant parasitic losses. Such copper shields are unnecessary in the Witton high frequency furnace because the external flux passes through the steel shroud, which at the same time forms the basis of a very strong mechanical construction.

CONSTRUCTION OF THE HIGH FREQUENCY FURNACE.

The general construction of the two furnaces built for the installation under consideration is shown in figs. 4, 5 and 6, these views being of the ½-ton furnace.

The water cooled inductor, fig. 4, consists of a number of turns of copper tube wound in four sections and connected in series. Each section of inductor is formed of one length of tube without any joints. Four sections are employed in order to enable sufficient water for cooling purposes to be passed through the inductor at a reasonable pressure. Insulation of the copper turns from each other is effected by treating the copper tube with a special insulating medium and covering this with a mica-silk tape. Further protection is given by means of asbestos tape which is impregnated with a moisture proof insulating medium. This extra protection is partly to meet thermal conditions and partly to afford greater mechanical strength. The method of insulating prevents moisture condensation on the cool copper tube, and also maintains the insulation at a low temperature in spite of the high temperature gradient between the charge and the copper inductor.

Copper bars are employed for connections between the inductor and the isolating plugs at the base of the furnace. By employing isolating plugs instead of flexible leads, an exceptionally rigid construction is obtained.

The external core D, fig. 1, is built up of silicon steel laminations. Its construction is shown in fig. 5.

FURNACE COOLING SYSTEM.

A closed water system is used for cooling the inductor coils. An electric motor driven pump circulates water from a conservator tank, first through a water cooler, then through the coils, and finally over water flow relays to the conservator tank. Air from outside the building is forced through the pipes of the cooler by an electric motor driven fan. A make-up water supply controlled by a valve facilitates the addition of water to the system to compensate for losses.

The four sections of the inductor of the larger furnace are fed in parallel, and the flow of water can be regulated to each section. The water passes to and from the inductor through rubber hose, which possesses sufficient flexibility to allow the furnace to be tilted without breaking the water columns, and insulates the parallel water paths from each other

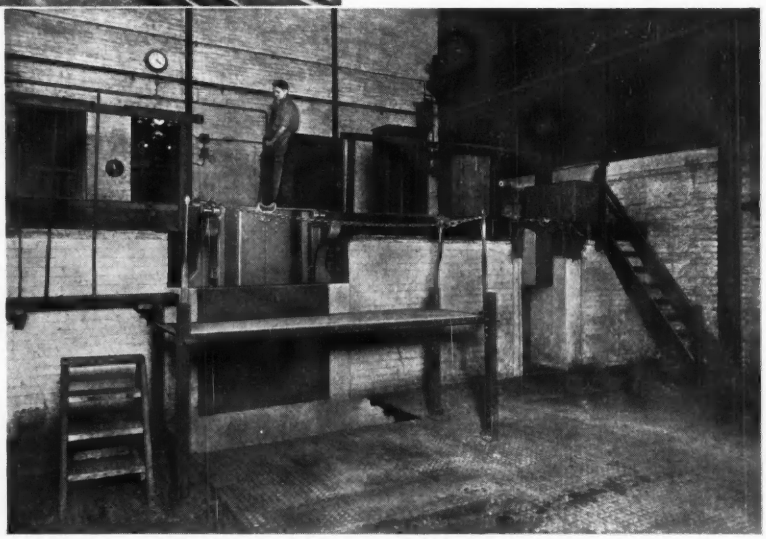


Fig. 8.—Near view of the furnaces—½-ton furnace on the left and smaller furnace on the right.

and earth. After passing through the furnace the water is run through thermostats and over water flow relays in each parallel water circuit. If therefore the water flow is reduced to a dangerous extent in any of the parallel paths these relays cut off power.

In the case of the smaller furnace there are two parallel water paths through the coil.

TILTING GEAR.

The tilting gear is of the lip-axis or nose pouring type. It is electrically operated and provision is made for automatically switching off the supply before any earthed metal work emerges through the working platform. The winch controlling the tilting gear is provided with an electro-magnetic brake, while a friction brake is automatically inserted during lowering operations.

Disconnection between the leads from the inductor and the supply is carried out by means of isolating plugs situated at the bottom of the furnace.

LAYOUT.

A general view of the melting shop in which the furnaces are installed is shown in fig. 7, and a near view of the furnace platform is given in fig. 8, in which the furnace control panel is indicated on the left hand. The tilting gear is immediately below the furnace, while the electrical machinery and control gear is arranged in an adjoining substation, views of which may be seen in figs. 10, 11, 15 and 17.

ELECTRICAL EQUIPMENT.

The capacity of the principal Witton high frequency furnace at Novo steelworks is ½ ton. It is rated at 150 kW for a melting time of 2/2½ hours, this rating being fixed to suit the convenience of the user. The voltage of supply is 1,200 and the frequency 1,000 cycles. In addition, there is installed a further furnace of this type with a capacity of 100 lbs. Apart from these furnaces, the following form the main sections of the electrical equipment :—

(1) A 150 kW motor-alternator set for converting the incoming power supply at 350 volts, 50 cycles, 3 phase, to 1,200 volts, 1,000 cycles single phase current, which is the system supplied to the furnace.

(2) Group of condensers for power factor correction.

(3) Control gear, which includes (a) switchgear for the incoming 350 volt 50 cycle supply and control of the motor of the motor generator set ; (b) furnace control panel, which controls the electrical operation of both furnaces ; and (c) the relays and remote controlled contactors for controlling and protecting the plant.

(4) Electrically driven pump for circulating the cooling water.

MOTOR-ALTERNATOR.

Views of the motor-alternator are shown in figs. 10 and 11.

Since it was decided to use a frequency of 1,000 cycles per second, the design of the alternator presented several problems. The speed was chosen at 1,450 r.p.m., this being a suitable speed for the 3 phase 50 cycle induction motor driving the alternator. The number of poles required at this speed to give an output frequency of 1,000 cycles is 84.

To make an ordinary salient pole alternator of this output with such a large number of poles is a practical impossibility owing to the very small pole-pitch which would have to be used. It was therefore decided to employ a homopolar type of machine. The stator contains two laminated cores each provided with a winding placed in slots. These windings have the output voltage induced in them and are connected to the terminals. In between the two cores is placed a single circular field coil for providing the D.C. excitation. The rotor has no windings, but consists of a solid steel cylinder with axial slots on the surface corresponding in number to the number of poles. When the rotor rotates, the flux at a given point in the stator varies as the rotor teeth pass it thus inducing a voltage in the stator winding.

In an ordinary salient pole alternator the external

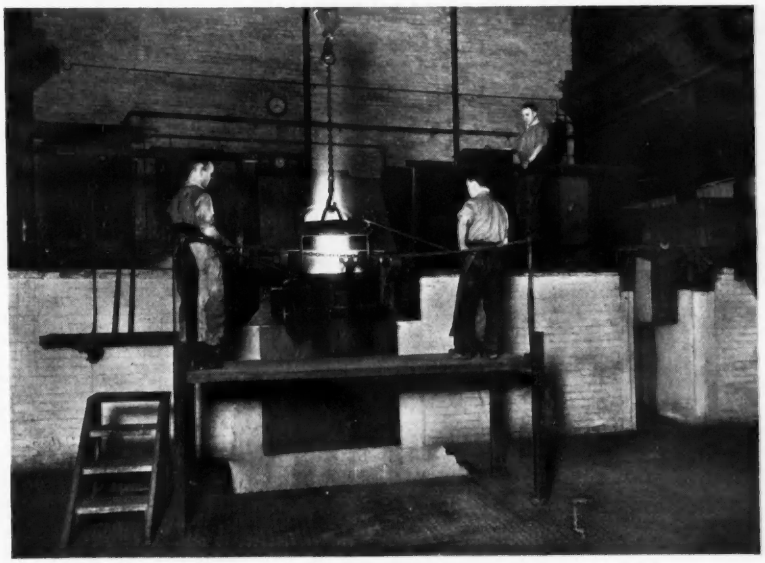


Fig. 9.—Start of the pouring operation.

field is extremely small since the north and south poles are all symmetrically balanced against each other. In the homopolar design, however, the external field may reach quite high values and it is important to use non-magnetic materials in all parts of the frame where magnetic leakage might produce losses.

Owing to the high frequency it was necessary to divide the stator conductors up into a large number of small sections in order to minimize the skin-effect. This was done by employing cables consisting of a large number of strands. The winding was also designed in such a way that the number of sweated joints is a minimum.

The most suitable voltage for the furnace and alternator was found to be 1,200 volts, and the output of the alternator is 150 kVA single phase. The motor is a standard 250 h.p. slipring machine running on the 350 volt supply at 1,450 r.p.m.

CONDENSER EQUIPMENT.

The inherent power factor of the Witton high frequency furnace is higher than that of other furnaces of similar general type, but it is impracticable, and undesirable, to build a generator to supply energy even at this increased power factor; hence condensers are provided to give the necessary wattless current and allow the alternator to operate at approximately unity power factor.

The power factor falls during the melting process as the charge changes from the solid magnetic state to the molten and non-magnetic state, the reactance of the furnace falling in accordance with the typical curve reproduced in fig. 12. Therefore, in order to maintain approximately unity power factor, the output from the condenser bank must be variable, and the sections of the condenser bank are arranged so that they may be added as and when required. The steps have been chosen so that the power factor may be maintained between .95 lagging and .95 leading. The condenser circuit arrangement in relation to the general scheme is shown to the right of fig. 14.

The condensers consist of a number of naturally cooled boxes containing oil immersed condenser spools of special design for high frequency voltages.

FURNACE EFFICIENCY.

There are so many variable factors which influence furnace efficiency that, when giving specific figures, due regard must be paid to service conditions. Furnace efficiency is governed by the following considerations:—

1. The time of melting.
2. The type of steel to be melted, its pouring temperature and the time allowed for the chemical reactions and refining.
3. The type of charge, *i.e.*, the size of raw material, method of packing and attention given to the closeness of packing during the preliminary melting stage.
4. The type and thickness of lining and its temperature at the start of the melt.
5. Efficiency of the generator plant and condensers and heavy current leads.

Certain points in these considerations call for comment. In regard to the time of melting, there are considerable heat losses which are dependent practically on time alone; it follows that with a lower kW rating, *i.e.*, a longer time of melt, the power consumption per ton must be higher. The curves shown in fig. 13 give an indication of the variation in electrical consumption per ton for furnaces of various sizes and ratings. Again, the rate at which the charge is melted at the beginning of the heat depends greatly on the type of charge. In order to ensure maximum efficiency it is desirable in general to fill one quarter of the furnace with heavy material, the remainder of the charge consisting of lighter material.

Of the two main types of furnace lining generally employed, *i.e.* acid and basic, an acid lining offers more resistance to the heat flow between the inductor and the charge than a basic lining, as the heat transference through the basic lining is about 60 per cent greater. The thickness of the lining also affects the heat loss as well as the closeness of coupling between the inductor and the charge.

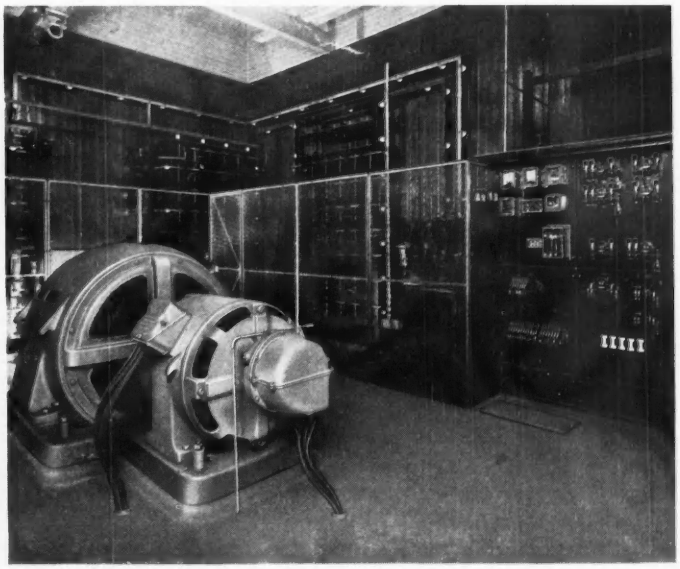


Fig. 10.—Part of the substation, showing the motor-alternator, contactor and protective gear panels, also a section of the condenser equipment.

Further, a considerable amount of heat may be lost during the period between pouring the molten charge and the start of a new charge, due to the heat lost by the lining on account of radiation and heat transference to the cooling water.

CONTROL SCHEME.

The general arrangement of the furnace power circuits is shown in fig. 14. Actually there are two incoming 350 volt 3 phase feeders, but only one is shown as the second supplies power for the operation of cranes and other appliances in the melting shop; this latter supply is controlled by the oil immersed drawout pillar illustrated on the left of fig. 15.

The feeder which supplies power to the furnaces is brought to the sheet steel cubicle seen on the right of fig. 13. Its equipment includes isolating links and an oil circuit breaker controlling the supply to the stator of the induction motor which is started by standard methods. A tapping from the feeder to a switch-fuse box feeds the auxiliaries and operating circuits for the furnace equipment.

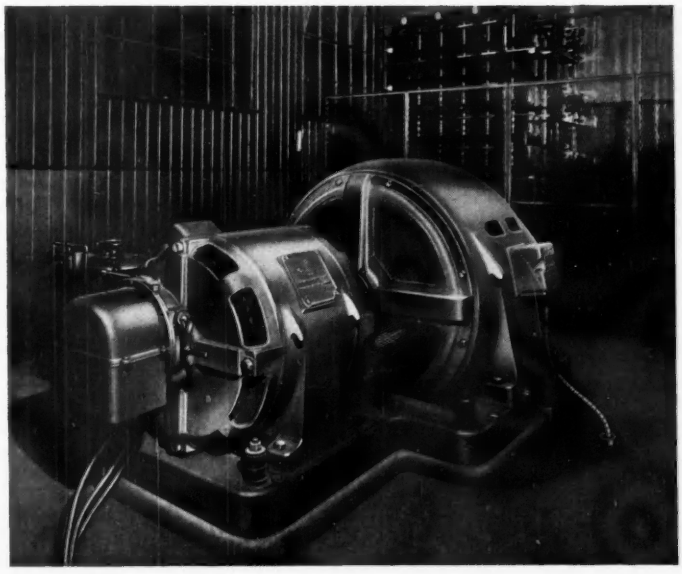


Fig. 11.—Near view of the 150 kW motor-alternator, with remainder of condenser banks.

It should be noted that the centre point of the generator is earthed through a current transformer, and also that the iron core of the furnace is earthed.

The generator supplies both the furnaces, a hand operated changeover switch, mounted in the basement connecting the required furnace. Each pole of this switch is in two parts to give sufficient current carrying capacity, and each blade of the switch is fitted with double pole push switches the contacts of which are connected to perform the following functions :—

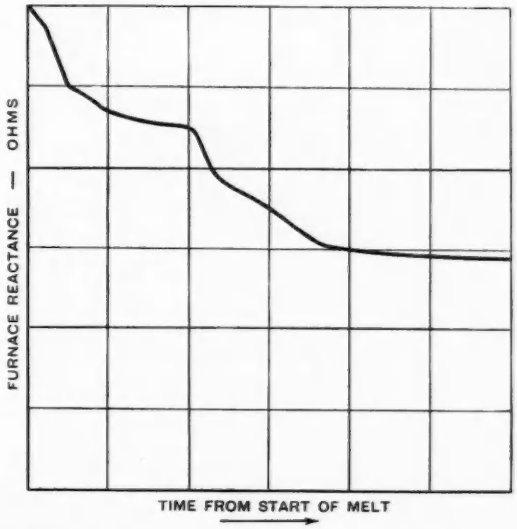


Fig. 12.—Curve of furnace reactance.

(a) To prevent the high frequency circuits being made alive unless the changeover switches are properly closed in one direction or the other.
(b) To shut down the high frequency supply immediately if an attempt is made to operate one of these switches when the high frequency power is on.
(c) To connect the appropriate water flow relays, thermostats and main furnace auxiliary contacts in circuit.
(d) To give lamp indication on the furnace control panel of the position of the changeover switches.

The high frequency current cannot be switched on until one or other of the furnaces is in circuit, otherwise the condensers are liable to be damaged.

Control of the high frequency circuits is effected from the furnaceman's panel, on which is mounted the following principal apparatus, fig. 16, reading from left to right and starting from the top left hand corner of the illustration :—

(1) Ammeter, power factor meter and voltmeter in the high frequency circuit.
(2) Ammeter in the generator field circuit.
(3) Operating handle for adjusting overload relay setting on either furnace; its operation also causes connections to be made which check the position of the changeover switch, and if these are in order the lamp indicators above are lighted.
(4) Control handle for switching the high frequency circuits on or off the furnace; lamp indication.
(5) Operating handle for field control.

(6) Emergency push button for stopping the motor-generator set; a red lamp above the push button shows when the set is running.

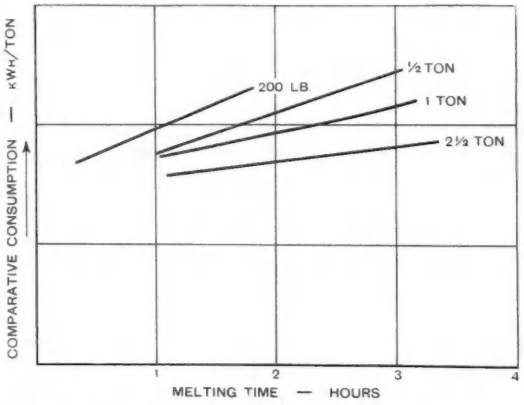


Fig. 13.—Curves indicating comparative consumption of furnaces of various sizes, with melting time.

(7) Operating handle for switching in or out additional banks of condensers.

When the motor-generator set and water cooling apparatus have been started, and the changeover switch has connected one of the furnaces to the power unit, the whole of the control is carried out from the furnace control panel.

When the furnaceman is ready for power to be switched on to the furnace, he momentarily operates the starting handle on the control panel. This initiates the following switching sequence, provided that interlocks and protective features indicate correct starting conditions :—

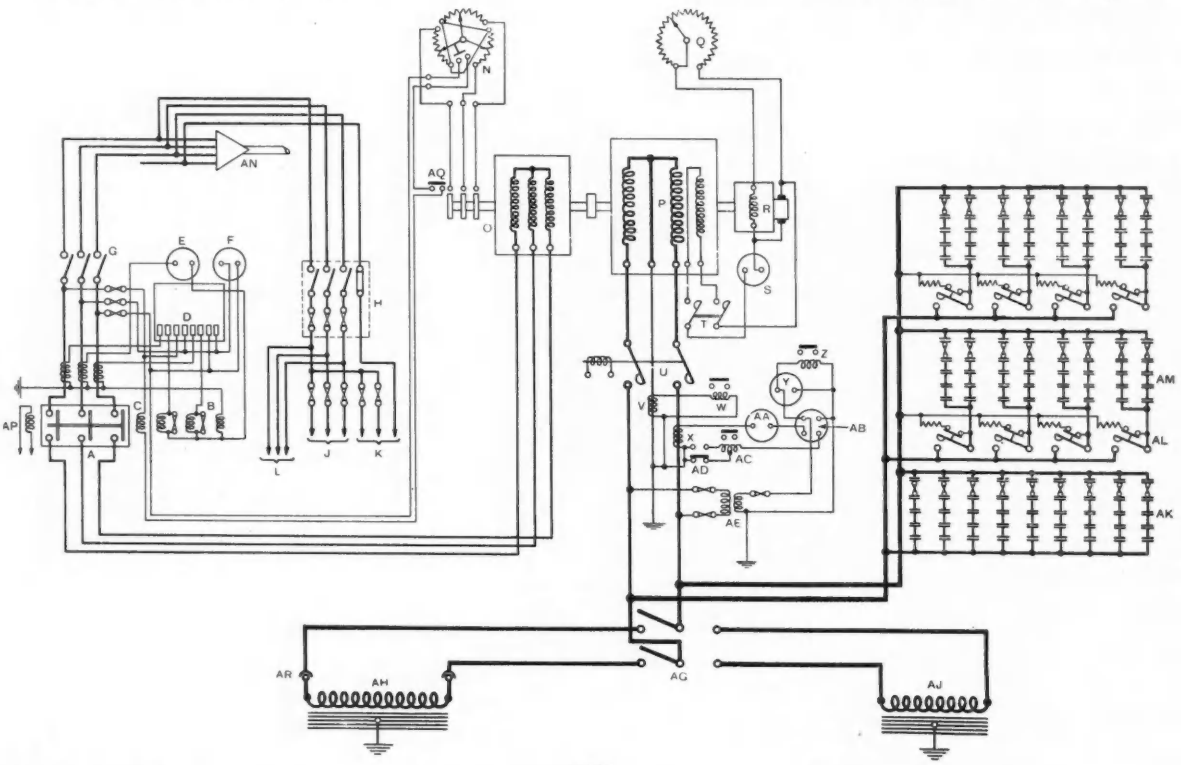
(1) The master contactor closes.

(2) The starting sequence drum controller motor becomes energized and the drum rotates to carry out successively the following operations :

(a) The closing of the main generator contactor which connects the high frequency supply from the alternator to the furnace.

(b) The closing of the alternator field contactor to excite the alternator.

(c) The completion of circuits whereby the alternator field may be varied as required.



KEY.

A	Main Oil Circuit Breaker.	**O**	Main Motor.	**AC**	Over Current Relay.
B	Overload Trips (with time limit fuses).	**P**	H.F. Alternator.	**AD**	Controller Contacts.
C	Interlocking Coil.	**Q**	Exciter Field Regulator.	**AE**	H.F. Potential Transformer.
D	Watt Hour Meter for Incoming Supply.	**R**	Exciter.	**AG**	Changeover Switches for Furnace Selection.
E	Ammeter.	**S**	Field Ammeter for Alternator.	**AH**	½ ton Furnace.
F	Voltmeter.	**T**	Field Contactor for Alternator.	**AJ**	100 lb. Furnace.
G	Isolating Links.	**U**	Main Generator Contactor (H.F. Circuits).	**AK**	Fixed Bank of Condensers.
H	Switch Fuse Box for Operating Circuits.	**V**	Earth Leakage Current Transformer.	**AL**	Contactors for Variable Banks of Condensers.
J	Auxiliary Motor Circuits.	**W**	Earth Leakage Relay.	**AM**	Variable Banks of Condensers.
K	Relay and Contactor Control Circuits.	**X**	Current Transformer for H.F. Instruments.	**AN**	Incoming 50 Cycle Feeder Cable.
L	Circuits for Water Cooling and Furnace Tilting Motors.	**Y**	Voltmeter.	**AP**	Main Oil Switch No Volt Coil.
N	Rotor Starter for Main Motor.	**Z**	Over Voltage Relay.	**AQ**	Interlock on Brush Lifting Device.
		AA	H.F. Ammeter.	**AR**	Isolating Plugs.
		AB	Power Factor Meter.		

Fig. 14.—General diagrammatic arrangement of control system.

(d) the stopping of the drum in the run position.

Since the alternator field is weak, the high frequency voltage will not rise very much, and to increase the power up to normal the field controller on the furnace panel must be operated in the increase power direction and held over until either the voltage or current has reached the marked value on the meters. As the heat proceeds the changing conditions in the furnace will alter the power input and this is adjusted from time to time to maintain the maximum power input.

The regulation of the condenser banks is also effected from the furnace control panel by contactor operation. When the power factor meter indicates a lagging power factor an additional bank of condensers may be added by operating the control handle provided on the furnace board for this purpose.

In this installation the direct switching of condensers at full voltage has been avoided. This gives a greater margin of safety.

Before changing the capacity of the condenser system, circuit arrangements are made to cut off the high frequency power and restore it again after altering the number of condenser banks in circuit. In order to simplify this control operation from the point of view of the furnaceman, and also to prevent switching mistakes and to effect such changes in as short a time as possible, a remote controlled sequence is initiated by operating (momentarily) the control handle either to raise or lower the power factor ; the operations which follow are :—

(a) The motor operated drum controller for cutting off the high frequency power is energized.
(b) This drum operates contacts to open the field contactor.
(c) After a suitable time delay the generator main contactor is opened and this drum controller stops.
(d) A second drum controller is started up to switch in or out a bank of condensers in accordance with requirements.
(e) The starting drum controller is again started to switch on power by closing the main generator contactor and field contactor, and power is restored to the furnace.

The above description of the control scheme applies in general to the operation both of the ½-ton furnace and the 100lb. furnace. It is obvious, however, that when changing over from one furnace to the other, certain points will have to be attended to, *e.g.* (1) the changing over of the controller on the furnace control panel so as to recalibrate the overload relay, and (2) the operation of a cock in the basement to divert the water from one furnace to the other, and certain similar operations.

PROTECTIVE FEATURES.

The plant is completely protected against faults which may occur on it or on the system to which it is connected. The following list summarizes these protective features.

(a) Emergency stop button.
(b) Over voltage protection (H.F. circuits).
(c) Earth leakage protection (H.F. circuits).
(d) Over current protection (H.F. circuits).
(e) Over temperature of inductor coils.
(f) No-volt protection (incoming supply).
(g) Overload protection (incoming supply).
(h) Failure of condenser.
(k) Limit switches.
(l) Overload, etc., on auxiliary motors.
(m) Incorrect operation of the control panel.

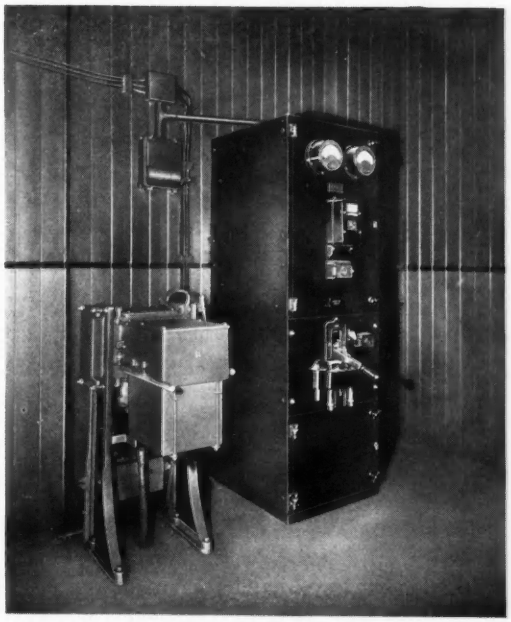


Fig. 15.—Switchgear controlling 350 volt incoming feeders.

Each of these protections will be briefly considered.

Emergency Stop Push Button.

The emergency push button is situated on the furnace control panel and has two contacts, the first a normally closed contact in series with the no-volt coil on the main incoming oil circuit breaker, and the second, a normally open contact, the closing of which energizes a tripping relay, which causes a rapid shut down. It will be seen, therefore, that the operation of the emergency push button immediately shuts down the power unit and takes the H.F. supply off the furnace.

Over Voltage Protection.

As a final protection against over voltage, an over voltage relay is fitted, which upon operation immediately cuts the power off the furnace. The operation is as follows :—

If the voltage rises to about 1,400 volts the over

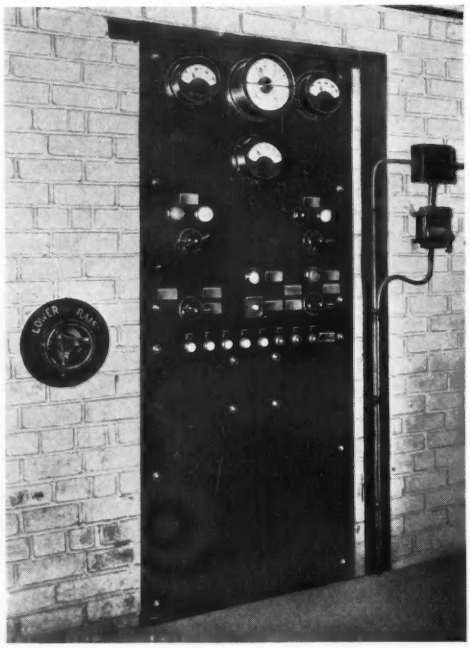


Fig. 16.—Furnace control panel.

voltage relay operates to close its contacts. This completes a circuit through the over voltage relay contacts, the lockout indicator coil, the tripping relay coil and a contact on the master contactor. The lockout indicator drops a flag to show the cause of the shut down and the tripping relay becomes energized. There are two normally closed contacts on the tripping relay, the opening of the first de-energizes the master contactor and initiates a shut down, but as the process takes some 6 seconds, a second contact immediately de-energizes the main H.T. contactor which opens and cuts power off the furnace at once. The plant cannot be run again until the tripping relay is reset by hand.

Earth Leakage Protection.

Reference has already been made to the fact that the mid point of the alternator winding is earthed through a current transformer. The iron core of the furnace is also earthed. If, therefore, any other point of the main H.F. circuits become earthed an earth current will flow and energize the current transformer in the earth connection from the centre point of the alternator. Across the secondary terminals of this transformer is connected a quick acting sensitive earth leakage relay. The operation due to the closing of the contacts of this relay is similar to that of the over voltage relay described above.

Over Current Protection (*H.F. Circuits*).

An inverse time limit overload relay is fitted in the secondary circuit of a current transformer in the H.F. circuit from the alternator. If the alternator delivers an over current for any reason, this relay operates the tripping relay and the operation is as described for the over voltage protection. When operating the $\frac{1}{2}$-ton furnace the settings of this relay are modified to suit operating conditions. When operating the smaller furnace a fixed lower setting of the relay is automatically switched into operation. Contacts on the controller for furnace changeover make this change.

Over Temperature of Induction Coils.

Water flow relays. In order to ensure that the water pump has been started and that the flow of water is established in the inductor coil, a water flow relay is fitted in the outlet from each section of the inductor coil, and if any one of these water flow relays has not operated, power cannot be switched on to the furnace. If when the furnace is running, for any reason the water flow ceases, the master contactor becomes de-energized and power is immediately cut off from the furnace.

Thermostats. As an additional precaution and in order to guard against overheating of the inductor coil due to too small a flow of water, each outlet is fitted with a thermostat which breaks the circuit to de-energize the master contactor and switch power off the furnace if the water issuing from the inductor is too hot.

No-volt Protection. (*L.T. 50 Cycle Incoming Supply*)

In the event of failure of the incoming supply, a no-volt coil becomes de-energized and trips the main circuit breaker to shut down the whole plant. Should the main control fuse blow, the same operation occurs, so that the plant cannot run uncontrolled.

Overload Protection (*Incoming 50 Cycle Supply*).

In each phase of the incoming supply there is an

Fig. 17.—Contactor and relay panel.

overload trip shunted by a time limit fuse so that a momentary overload does not cause an unnecessary shut down. A sustained overload on the motor of the motor alternator set will, however, trip the oil switch and shut the plant down.

Failure of Condenser.

Across the 1,200 volt H.F. supply there is a set of five condenser units connected in series to form a condenser bank. If any one of these units fails by shorting or earthing, the fuse in series with that bank is blown and that bank is cut out.

Limit Switches.

All apparatus which can be overwound is fitted with limit switches to prevent damage due to any tendency to overwind.

Overloads, etc., on Auxiliary Motors.

The water pump motor, fan motor and tilting winch motors are all protected by time delay overload devices which operate to protect the motors in case of a fault on any of the above apparatus. The pump and fan motors also have no-volt protective features, being controlled in each case by contactors which become de-energized on failure of supply. The smaller motors for drum controllers are protected by fuses.

In conclusion acknowledgment is due to J. G. Widdowson, Esq., Managing-Director of Jonas & Colver (Novo), Ltd., for permission to publish this article and the illustrations which accompany it.

"Osira" Lighting at Richmond, Surrey.

Kew Road, Richmond, Surrey, illuminated by 400-watt "Osira" lamps housed in lanterns of the "Tunbridge Wells" type. A total of 346 400-watt "Osira" lamps are used in this new lighting installation at Richmond which replaces a gas lighting scheme.

Magnetron Valves for Ultra-Short Wavelengths.

By E. C. S. MEGAW, B.Sc., D.I.C.

Research Staff of the M.O. Valve Company, Ltd., at the G.E.C. Research Laboratories, Wembley, England.

INTRODUCTION.

THE increasing technical interest in oscillations of ultra-short wavelength, which has been evident in recent years, has brought to light the inherent limitations of the familiar triode circuits

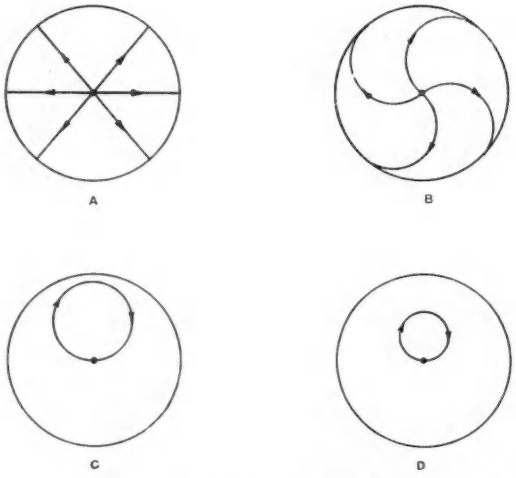


Fig. 1.—Electron paths in a cylindrical diode
(A) without magnetic field
(B) with weak magnetic field
(C) with critical magnetic field
(D) with strong magnetic field

in producing, amplifying and detecting such oscillations, and has encouraged the examination of other possible methods. These limitations arise from the inter-electrode capacities and the electrode lead inductances on the one hand, and from the finite transit time of the electrons constituting the current in the valve on the other. They exist, to a greater or less extent, in any kind of thermionic valve, but it has been found that they are less serious in the type of valve to be described in this article, of which the characteristic feature is that the electron paths are modified by the presence of a constant magnetic field.

The ultra-short wave range may be taken as lying between 10 metres and 1 centimetre; the part of this range below 1 metre is often called the micro-wave range. For purposes of comparison, the practical wavelength limit of conventional triode circuits may be taken as about 1½ metres for the production of powerful oscillations, or of a useful amount of amplification, and about 50 cm. for detection. The corresponding figures are about 75 cm. and 10 cm. respectively for magnetron circuits. The latter cannot, however, be used as amplifiers in quite the same way as triodes and, although magnetron amplification is possible, it has not yet received much attention. Weak oscillations can be produced and detection effected down to about 10 cm. by special triode circuits, using positive grid voltage and negative anode voltage, but the efficiency is considerably lower than that of the corresponding magnetron circuits. The shortest wavelength ever produced under laboratory conditions, is about 1 cm. for the magnetron and 3 cm. for the triode. The chief use of the magnetron has been as an oscillation generator, and it is with this use that the present article is primarily concerned.

The practical applications of the ultra-short waves below about 3 metres, for which magnetron valves are particularly suitable, have as yet been but slightly explored. Among them may be mentioned: short-distance radio communication circuits, particularly for point-to-point working, including television circuits; radio beacons, particularly for

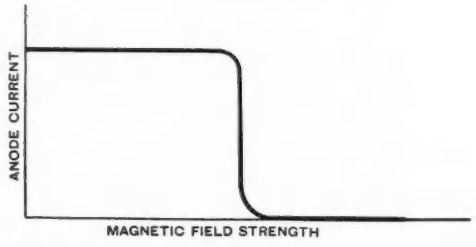


Fig. 2.—Relation between anode current and magnetic field strength at constant anode voltage.

aircraft; production of local heating, and possibly other effects, in medicine; and physical applications such as the study of dielectrics at very high frequencies. The general principles of the action and use of magnetron valves are set out in this article for the guidance of those who wish to examine the possibilities of this new and promising field.

THE USE OF A MAGNETIC FIELD IN VALVES FOR GENERATING ULTRA-SHORT WAVE OSCILLATIONS

If a cylindrical diode is placed in a uniform magnetic field parallel to the electrode axis the flow of electrons from cathode to anode, when the latter is positively charged, is modified by the magnetic field as indicated in fig. 1. The electrons experience a deflecting force proportional to their velocity and to the field strength, so that they cease to reach the anode when the field strength exceeds a critical value given approximately by

$$H = \frac{\sqrt{180\,E_a}}{d_a} \quad .. \quad .. \quad .. \quad (1)$$

where H = magnetic field strength (gauss),
E_a = anode voltage,
d_a = anode diameter (cm.).

If anode current, at constant voltage, is plotted against field strength a "cut-off characteristic" results, as shown in fig. 2. Alternatively, if the anode voltage is varied with a constant field, equation (1) defines the critical anode voltage.

Methods of Producing Oscillations with Magnetron Valves.

It is evident from fig. 2 that the magnetic field can be used to control the anode current in a similar way to the grid voltage in a triode. The original magnetron oscillator worked in this way, but its action was limited to long wavelengths by the inductance of the coils carrying the alternating field current, and it did not prove an economic competitor of the triode oscillator. In the methods of use to be described a constant magnetic field is used to control the direction rather than the magnitude of the electron current. Two distinct methods of use are possible. In the first, a negative resistance effect arising from the deflection of the electrons by the magnetic field is used to produce oscillations whose frequency is substantially equal to the natural frequency of a tuned circuit connected to the valve. In the second, the frequency is substantially equal to the rotation frequency of the electrons about the lines of magnetic force, and the oscillations are maintained by a transformation of part of the kinetic energy of the moving electrons into potential energy stored in the oscillating circuit. The general mechanism of both these oscillations, which are appropriate to rather

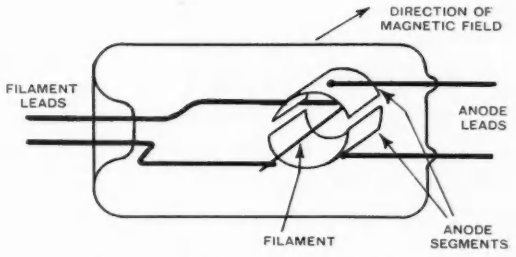


Fig. 3.—Split anode magnetron.

long and to extremely short wavelengths, respectively, is not difficult to understand, though precise calculation from first principles is, as with most processes in practical thermionic valves, a matter of great difficulty. It is, however, also possible to generate oscillations of intermediate wavelength which share certain characteristics with each of the kinds of oscillation just mentioned, but they are not so well understood. Before attempting to discuss this intermediate range, which from the practical point of view is the most important of all,

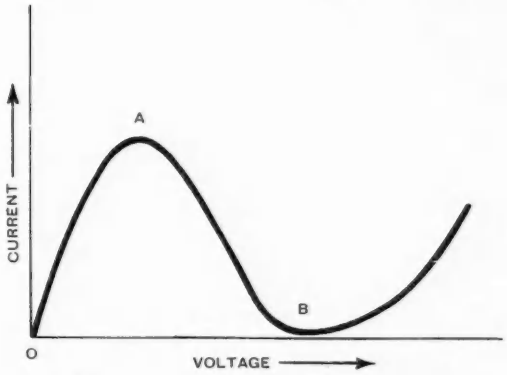


Fig. 4.—Dynatron characteristic of a split anode magnetron.

the mechanism of the long wave and the extremely short wave oscillations will be described in a little more detail.

NEGATIVE RESISTANCE OR "DYNATRON" OSCILLATIONS.

Negative Resistance in the "Split Anode" Magnetron.

The modern magnetron valve, in its simplest form, is a cylindrical diode, of which the anode is divided into two or more equal segments separated by narrow gaps. The electrode arrangement of such a valve with two anode segments is shown in fig. 3. The function of valves with more than two anode segments will be discussed later. This arrangement is often called a split anode magnetron. The valve operates in a magnetic field with the electrode axis approximately parallel to the lines of force.

Static characteristics of such a valve show some interesting features. If a constant positive voltage with respect to the filament is applied to one anode segment, the relation between voltage and current for the other segment is of the type shown in fig. 4, provided the magnetic field strength is above the critical value corresponding to the fixed voltage. This characteristic has a range *AB* of negative resistance and is quite similar in form to the dynatron characteristic arising from secondary electron emission in a screen-grid valve. The explanation of the negative resistance characteristic of a magnetron is briefly as follows:—When the voltage on the second segment is small it receives very few electrons,

but a large current flows to the first (fixed voltage) segment, because the electric field arising from the potential difference between the anode segments opposes the deflection caused by the magnetic field. As the voltage on the second segment is increased towards that on the first, the electrons are increasingly deflected by the magnetic field so that, at first, they reach the second segment in increasing numbers. When, however, the segment voltages are approaching equality the deflecting action is so far increased

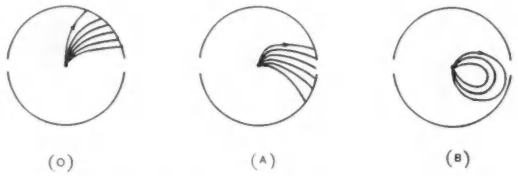


Fig. 5.—Changing electron paths corresponding to the negative resistance region.

that the current to both segments falls towards zero, since the magnetic field strength exceeds the critical value corresponding to the voltage of the fixed segment. No secondary emission phenomena are thus necessarily involved and experiment shows that they are, in fact, of no practical importance at long wavelengths. Fig. 5 gives a diagrammatic illustration of the electron paths corresponding to the points *O*, *A* and *B* in fig. 4; the upper anode segment is here supposed to have the fixed voltage while that of the lower segment is increased.

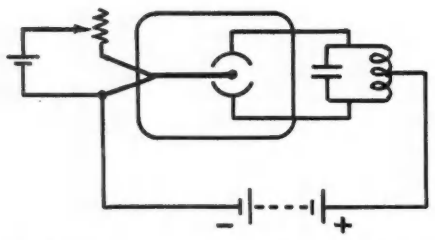


Fig. 6.—Symmetrical split anode magnetron circuit.

It is clear that this mechanism will enable oscillations to be maintained in any tuned circuit connected between one anode segment and its high tension supply, provided the losses and the natural frequency of the circuit are not excessively high. In practice, negative resistances down to a few thousand ohms can be obtained.

The Symmetrical Magnetron Circuit.

If an oscillatory circuit is connected between the anode segments (fig. 6), so that oscillations in it produce equal and opposite voltage changes on the two segments, a similar negative resistance characteristic is obtained for each segment. This is the circuit arrangement usually employed for short wave working. The condition for maintaining oscillations is now rather different. Suppose, at any instant, the voltage and current are $E_a + e$ and i_1 for one segment, and $E_a - e$ and i_2 for the other, E_a being the H.T. voltage applied to the centre of the circuit, and e being half the instantaneous p.d. between the anode segments, then the instantaneous power supplied to the valve by the circuit is

$$(E_a + e)\, i_1 + (E_a - e)\, i_2$$
$$= E_a\,(i_1 + i_2) + e\,(i_1 - i_2).$$

Now $E_a\,(i_1 + i_2)$ is the power taken from the H.T. supply. Hence the valve will take power from the circuit when $e\,(i_1 - i_2)$ is positive, and will give power to the circuit when $e\,(i_1 - i_2)$ is negative. The condition for oscillation is that the integral of $-e\,(i_1 - i_2)$ or $e\,(i_2 - i_1)$, averaged over a high frequency cycle, shall be algebraically greater than the losses in the circuit, including any power supplied to a load. The existence of ranges of negative slope is not enough; the current reaching the less positive anode segment must be greater than that reaching the more positive segment over an appreciable range of e.

To study the oscillation performance of this circuit it is convenient to plot the sum $(i_1 + i_2)$ and difference $(i_1 - i_2)$ of the segment currents against e for values of magnetic field strength above the critical value, equation (1). Curves of the type shown in fig. 7 are obtained. The input to the valve is given by

$$\frac{1}{T}\int_0^T E_a\,(i_1 + i_2)\,dt,$$

and the output by

$$-\frac{1}{T}\int_0^T e\,(i_1 - i_2)\,dt,$$

where T is the oscillation period. If a sinusoidal variation is assumed for e, the input and output can easily be computed by graphical integration of the static characteristics for any given operating conditions.

A study of the static characteristics has shown that so long as the current is limited only by space charge they can be represented approximately by simple linear equations very similar to the approximate equation for a family of triode characteristics. When either voltage E_a or e is so high that the current is limited by filament temperature, the negative resistance characteristics disappear. These equations enable the approximate long wave performance of the oscillator to be predetermined rapidly under any required conditions, and hence they are very useful in comparing its behaviour at long wavelengths with that at wavelengths so short that the static characteristics are not valid. The results of this study show that the maximum output obtainable from a split anode magnetron at long wavelengths can never exceed, and in general is less

than, the output of a triode having the same anode voltage and filament emission. Another interesting result is that the efficiency at which this output is obtained decreases as the width of the gaps between the anode segments is increased and is approximately proportional to $\cos 2\beta$, where β is the angular width of the gaps.

ELECTRON RESONANCE OR "ELECTRONIC" OSCILLATIONS.

We pass now to the opposite end of the wavelength spectrum in which magnetron valves can be used, to consider the case in which the electron transit time, instead of being negligible, is the primary factor on which the oscillation mechanism depends.

If the magnetic field of a magnetron is slightly greater than the critical value, the electrons describe roughly circular paths about the lines of magnetic force, skimming the anode surface, fig. 1 (c). The angular velocity of the electrons is proportional to the magnetic field strength, and the wavelength corresponding to their rotation period is approximately

$$\lambda = \frac{12{,}000}{H} (cm.) \quad .. \quad .. \quad (2)$$

where H is the magnetic field strength in gauss. If an oscillatory circuit tuned to this wavelength is connected either between anode and filament of a simple cylindrical magnetron or between the anode segments of a split anode magnetron, oscillations are set up in it at the electronic frequency. The behaviour of the oscillator is similar in both cases.

"Transit Time" Effects in Rapidly Varying Electric Fields.

The mechanism by which oscillations of this kind are maintained has been the subject of much discussion, in which the nature of the fundamental process has sometimes been obscured by the analytical complexity of particular cases. The fundamental principle on which the mechanism depends is simply this: the change in kinetic energy of a charged particle in moving freely between two points in a varying electric field may be either greater or less than the difference in potential energy between the two points. The following argument shows that this involves no violation of the principle of the conservation of energy.

In the simplest case of an electron with charge e and mass m moving freely from rest through a one-dimensional electric field, the velocity of this electron after a lapse of time T is

$$v = \frac{e}{m} \int_0^T F.dt$$

where F is the electric field strength acting on the electron at any instant t. If F varies with position only, but not explicitly with time, it follows that

$$v = \sqrt{2 \frac{e}{m} V}$$

where V is the potential difference through which the electron has moved; this is only another way of stating that the final kinetic energy is equal to the initial potential energy and that total energy of the electron is constant. In valves operating at long wavelengths the changes in electric field strength occur so slowly, compared with the speed of the electrons, that their effect is negligible. If, however, F varies sufficiently rapidly, as is the case at very short wavelengths, the velocity of an electron on arrival at any electrode may be either much greater

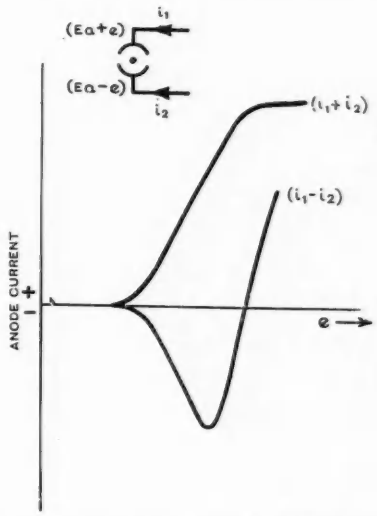


Fig. 7.—Relation between sum and difference of segment currents, and voltage change on each segment.

or much less than the value corresponding to the electrode potential at the moment of arrival, depending on the time changes in field strength which have occurred during its transit. When such changes occur the energy lost (or gained) by each electron is stored in (or taken from) the electric field, and so constitutes an output to (or a load on) the circuit connecting the electrodes which form the boundaries of the field.

Here we have the general explanation not only of electronic oscillations, but also, at first sight, such surprising phenomena as: electron bombardment of, and secondary emission from electrodes at a large and constant negative potential with respect to the electron source, or conversely, the arrival of large electron currents at highly positive electrodes with a liberation of heat much smaller than that corresponding to the product of voltage and current; and the maintenance of strong oscillations in a circuit connected to electrodes between which no appreciable direct current flows. These effects are

no mere academic curiosities ; they are often of great importance in the practical utilization of ultra-short wave generators. In studying the behaviour of such generators it is essential to remember that the product of instantaneous electrode voltage and conduction current is no longer a measure of the power ; the displacement current induced by the electron motion must also be taken into account, since the real component of this current corresponds to the change of electron energy during transit.

The Mechanism of the Electronic Oscillations.

The essential condition for maintenance of electronic oscillations is that on the average more energy shall be given to the circuit by the electrons which are retarded by the alternating field than is absorbed by those which are accelerated. There is no fundamental reason to suppose that this condition could not be fulfilled when electrons travel directly from filament to anode (instead of describing some sort of oscillatory path) or when the circuit frequency does not correspond exactly to any periodic motion of the electrons ; it has in fact been suggested that the whole idea of electron resonance is irrelevant. However, in the magnetron case at least, there is strong experimental evidence in its favour. Not only is the observed oscillation frequency always close to the calculated electron rotation frequency, but its variations with anode current and anode voltage agree in direction and roughly in magnitude with those calculated for the electron frequency. Further, the oscillations persist, with little change in

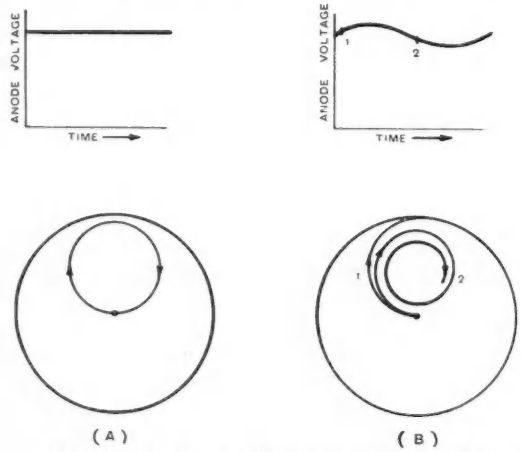


Fig. 8.—Electron paths under conditions for electronic oscillations.

frequency, when the external circuit is widely detuned and they appear to be still maintained in the absence of any oscillatory system other than the electrons themselves. The output is greatest when the anode voltage is just below the critical value $\frac{(d_a^2 H^2)}{180}$ and the oscillations cease when all the emitted electrons travel directly to the anode.

On the electron resonance hypothesis a plausible explanation can be given of an important effect which is otherwise very puzzling ; the maximum output (from a valve like fig. 3) is always obtained when the electrode axis is inclined at an angle of a few degrees to the direction of the magnetic field and, if the anode is so long that the electric field is substantially undistorted near its centre, no appreciable output is obtained with zero inclination. Before giving this explanation we note two experimental facts : (1) the width of the anode gaps has no important effect on the efficiency, and (2) the efficiency is greatest with small anode currents and falls rapidly when the space charge density becomes large. These effects are precisely the opposite of what holds for the long wave dynatron oscillations. They suggest that it is only the transfer of energy from the electrons to the circuit during their transit, and not the part of the anode on which they arrive, which decides whether or not oscillations can be maintained. The effects also suggest, and other experiments confirm, that the essential mechanism is much the same whether a split anode or a complete cylindrical anode is used. For convenience we shall consider the latter.

Fig. 8 (a) indicates the path of an electron when the magnetic field is parallel to the filament and the anode voltage is just below the critical value so that no electrons reach the anode. The path is nearly a circle so long as the filament diameter and space charge density are small. If a small alternation, of the electronic frequency, is superimposed on the anode voltage, and in practice thermal agitation of electrons in the oscillatory circuit will always provide such an initial alternation, electron paths of the type shown in fig. 8 (b) will result. Electrons starting from the filament at a point such as 1, near the beginning of the positive half cycle, will gain energy enabling them to reach the anode where their total energy is dissipated as heat, while other electrons starting at a point such as 2, about half a cycle later, will give up energy to the circuit and travel in a closing spiral. This cannot, however, continue for long because the electron path lies more nearly with each successive loop in a region of constant potential and the rotation frequency increases towards a maximum value corresponding to $\lambda = \frac{10{,}650.}{H}$ The phase of the useful group of electrons relative to the voltage alternation thus changes continuously until they start gaining energy from the circuit. The amplitude of their path then increases until they reach the anode with almost their original energy. The net output is likely to be vanishingly small. To obtain the maximum possible output we require to shift the axis of the spiral path continuously towards the anode so that the useful electrons just reach the anode when their amptitude (and energy) has fallen to its lowest value. Now if the magnetic field is slightly inclined

to the electrode axis the spiral path becomes roughly a helical one about an axis parallel to the field and therefore approaching the anode surface. The adjustment of the field angle is thus a convenient way of ensuring a maximum transfer of the energy given to the electrons by the source of anode voltage, to the oscillatory circuit. A similar result can be obtained by using an axial electric field, provided by positively biassed electrodes at the ends of the anode, to give the electrons an axial component of velocity. In this way the optimum condition can be obtained for a greater number of electrons simultaneously and the efficiency is increased.

"Axial" Electronic Oscillations.

It may be mentioned that another mode of electronic oscillation, in which the characteristic frequency depends on an electron motion roughly parallel instead of perpendicular to the electrode axis, is possible in magnetron valves. The corresponding wavelength is usually of the order of a few metres and the oscillations can be detected without any resonant circuit connected to the magnetron. These oscillations appear to be of no practical value as a source of power and their energy is so low as to have no appreciable effect on dynatron oscillations of similar wavelength even though the two are generated together, as is often the case. In magnetron receivers, however, they may be a serious source of noise with incorrect adjustments.

THE "INTERMEDIATE" WAVELENGTH RANGE.

Behaviour of Magnetron Valves in the Intermediate Range.

The intermediate wavelength range may be defined as extending from the wavelength at which the effect of electron transit time begins to make the dynamic characteristics of the valve differ appreciably from the static dynatron characteristics to the wavelength at which the negative resistance effect disappears. In practice the range is roughly from 10 metres to 50 cm. The behaviour of the oscillator (fig. 6) as the circuit wavelength is continuously varied, from long waves downwards, is illustrated in fig. 9. These curves apply to a constant magnetic field strength of about twice the critical value, but they are generally similar for any field strength between about 1.25 and 5 times the critical value. The circuit impedance is assumed to be adjusted (by varying the load coupling) to match the effective impedence of the valve, so as to obtain the greatest output at each wavelength. The most striking fact about these curves is that as the wavelength is decreased into the intermediate region the output and efficiency increase at first, maxima being reached not far above the minimum wavelength. The reduction of the impedance of the equivalent generator by which we can represent the valve is also valuable since it results in less power being lost in the oscillatory circuit as distinct from the useful load. These characteristics are primarily responsible for the good performance of magnetron oscillators at ultra-short wavelengths. In the conventional triode oscillator the output and efficiency fall continuously as the wavelength is reduced.

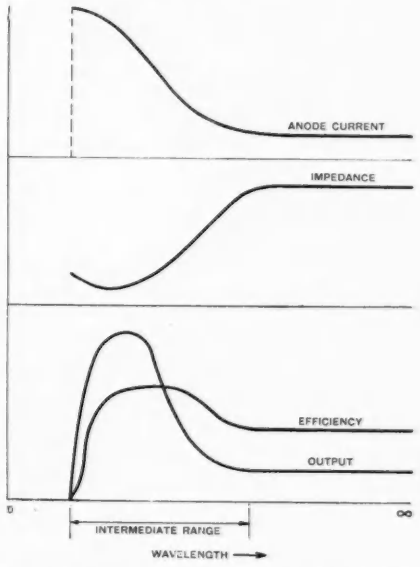


Fig. 9.—Behaviour of a magnetron oscillator in the intermediate wavelength range, showing the effect of electron transit time.

The wavelength at which the maximum output is obtained is roughly proportional to the magnetic field strength. The magnetic field may be thought of as a means for varying the transit time to suit the desired wavelength. Even apart from economic difficulties in producing very large fields this process cannot, however, be extended to indefinitely long wavelengths. The output reaches an absolute maximum at a wavelength corresponding to 2 or 3 times the critical field. At longer wavelengths, the optimum field increases less rapidly than the wavelength, and becomes less sharply defined, while the output gradually falls to the value determined by the static characteristics (fig. 17).

Two suggestions have been put forward to explain the existence of an optimum transit time. The first regards the mechanism of oscillation as essentially the same as at long wavelengths, ignores the change of electron energy during transit, and seeks to show that more electrons reach the part of the anode having, instantaneously, the lower potential when the transit time has its optimum value. The second regards the mechanism as essentially different from the long wave case and seeks to explain the optimum as solely due to the change of electron energy during transit.

Neither of these hypotheses seems able to explain all the observed facts, but it is probable that there

is an element of truth in both. The following well established experimental results throw some more light on the matter :—

(1) There is no discontinuity in the oscillation between the longest wavelengths and the minimum indicated in fig. 9 provided the load impedance is adjusted for maximum output.

(2) The efficiency increases as the gaps between the anode segments are reduced, at a similar rate throughout this wavelength range.

(3) The absolute optimum field strength in the intermediate range is about the same as at long wavelengths.

(4) The observed efficiency near the minimum wavelength is greater than can be accounted for by the measured ratio of peak to mean anode voltage, assuming any dynamic characteristic whatever, without introducing a loss of electron energy during transit.

(5) The presence of a number of electrons which have *gained* energy from the circuit is shown by an increase in filament temperature as the minimum wavelength is approached. This increase has been proved experimentally to be due to electron bombardment.

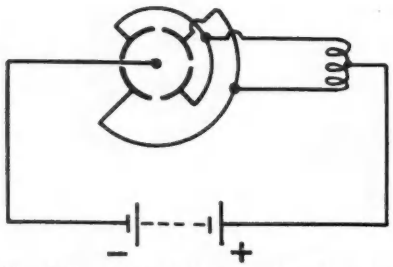


Fig. 10.—Circuit connections to 4-segment anode.

The only reasonable interpretation to put upon these facts would seem to be that the intermediate oscillations are of the same general type as the long-wave oscillations but that the dynamic characteristics are profoundly modified by transit time effects and, further, that these effects are such that both the angular deflection and the energy change of the electrons are important. In the absence of any compendious term to express this state of affairs the oscillations in the intermediate region may, for brevity, be called negative resistance or dynatron oscillations to distinguish them from the electron resonance or electronic oscillations for which only the change of electron energy during transit is important.

4-Segment Magnetron Valves.

The two hypotheses advanced to explain what happens in the intermediate region both lead to expressions for the optimum condition which suggest that shorter wavelengths can be obtained by using more than two anode segments. The first expression is derived on the assumption that the electron paths are nearly the same as under static conditions so that the angular velocity is proportional to the field strength. The general idea is that, in the optimum condition, electrons which just miss an instantaneously negative part of the anode on their first approach describe loops in such a way that the part of the anode on which they eventually arrive is also instantaneously negative, relative to the mean anode voltage. So the number of useful electrons is increased. The expression derived for the optimum wavelength in centimetres is

$$\lambda_0 = 1.07 \times 10^4 \frac{n}{H} \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

where n has the value 4 for a 2-segment anode and 2 for a 4-segment anode; the anode voltage must be approximately equal to the critical value given by equation (1). In practice, this expression combined with equation (1) gives approximately the correct minimum wavelength but nothing more.

The second expression gives the optimum wavelength as

$$\lambda_0 = \frac{236\, d_a^2\, H}{k\, E_a} \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

where k is the number of pairs of segments. This expression is obtained as the condition for maximum energy loss for electrons having a constant angular velocity equal to that of one of the components into which the alternating electric field between the anode segments can be resolved, assuming that the radial field is negligible, so that the electron paths are spirals with the filament as axis. Although the actual electron paths must be much more complicated, this second expression represents the observed results to a fair degree of accuracy between the minimum and the optimum wavelengths for a given valve, and these wavelengths, in practice, are reduced by a factor of about 2 by using 4 anode instead of 2 anode segments. The circuit connections are then as shown in fig. 10. The use of more than 4 segments is found to be of little practical value.

It is found that the position of the filament is particularly important in 4-segment valves. If it is central in the anode and the magnetic field is uniform the useful wavelength range is limited to a narrow band in the neighbourhood of the minimum. If, however, it is eccentric, by about 1/5 of the anode radius, towards one of the anode gaps, the useful wavelength range is of similar width to that obtained with a 2-segment anode but the minimum wavelength is increased by about 30 per cent. With a central filament this effect can be simulated by distorting the magnetic field, for example, by moving the anode axis from the axis of symmetry of the field, with similar results but much lower efficiency. The effect appears to be due to the reduced tangential component of electric field close to the anode axis, in a 4-segment, as compared with a 2-segment system.

The static dynatron characteristics of a 4-segment valve are also, in general, less good as regards possible output and efficiency, probably for the same reason. With either of the suggested explanations of the optimum wavelength it is to be expected that the output-wavelength characteristic of a 4-segment valve will have a minimum on the long-wave side of the maximum (fig. 9) at about the optimum wavelength for a 2-segment valve under the same conditions. This is found to be the case.

Electron Bombardment of the Filament and its Results.

There is one other characteristic feature of operation in the intermediate region which must be mentioned. To obtain the lowest minimum wavelength the highest permissible anode voltage is normally used and the input is limited by the available filament emission. It is found that the mean anode current on oscillation can rise to values comparable with, and even much greater than, the original total emission as the minimum wavelength is approached (fig. 11). A part of this rise may be due to anode current flowing during a greater fraction of the H.F. cycle than at long wavelengths, but the greater part is a result of the electron bombardment of the filament which has already been mentioned. The available emission is increased by the resulting rise in filament temperature and by the emission of secondary electrons. The bombardment must not be allowed to increase the emission too far or an unstable condition may result, leading to a heavy overload on the valve. Life test results near the optimum wavelength, with mean anode currents about equal to the original emission, suggest that the contribution from secondary emission may be quite important. Although the number of secondaries emitted per primary cannot be much greater than 1 for a tungsten filament it is not improbable that a cumulative "electron multiplication" takes place, so that the effective emission for a given filament power and life is increased.

The Use of Grid Electrodes.

With a simple electrode system (fig. 3 or fig. 10) the electron bombardment of the filament can, however, be a serious nuisance, in that the oscillations if stopped under conditions for maximum output, will not start again unless the field is reduced (fig. 11a). This effect becomes more pronounced as the optimum field strength increases; it depends on the fact that the effective valve impedance falls as the oscillation amplitude increases. This is the case at high field strength even without filament bombardment but the effect is exaggerated as the bombardment increases. An almost complete cure for wavelengths from the optimum downwards has been effected by fitting a special form of grid (fig. 12), held at about filament potential, in the case of 2-segment valves. The stability of the oscillator is considerably improved by this means and the efficiency is also increased at the shorter wavelengths (fig. 11b). The application of this device to 4-segment valves has not yet been fully explored.

OPERATING CHARACTERISTICS OF MAGNETRON VALVES.

The practical operating conditions for magnetron valves as ultra-short wave generators are summarized

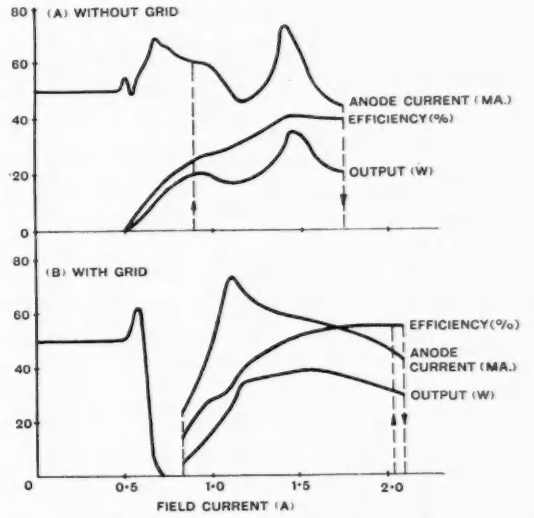


Fig. 11.—Improvement of stability and efficiency by grid at filament potential.
E_a=1200 V., d_a = 1 cm., λ = 2.5 metres.

in quantitative form in Table 1. While the data in the table are not exact they form a useful guide to the performance and requirements of any given valve; they also enable the user to decide which type of valve and method of operation is best suited to his particular needs; and lastly, they indicate the limits of practical performance with present day technique. The data given under dynatron oscillations refer to operation in the intermediate wavelength region. No reference to long-wave working is included. The long-wave output of a typical magnetron capable of giving 50 watts output at 3 metres is only about 7 watts. If, however, the filament emission were increased from the normal value of 80 mA to about 400 mA the long-wave output would be of the order of 60 watts and the performance quite comparable with a similar triode. The use of dull-emitter filaments, capable of giving such large emissions with the small dimensions required for ultra-short wave working, leads to difficulties on account of electron bombardment and the useful operating range of magnetron valves is there-

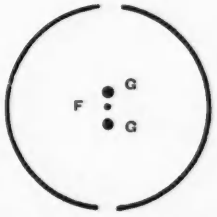


Fig. 12.—Arrangement of grid wires.

fore normally confined to ultra-short wavelengths. In Table 1 the maximum wavelength is roughly that at which the available output has fallen to 1/3 of its value at the optimum wavelength. In this connection it is perhaps appropriate to remark that the range from 1 metre to 3 metres is, in terms of frequency difference, much wider than the whole of the radio frequency spectrum excluding ultra-short wavelengths.

Power Output Limits.

Table 1 shows that, in general, a reduction of optimum wavelength involves a reduction in anode diameter and in efficiency. There are also definite limitations, both physical and economic, on anode length. The maximum power obtainable with a given type of construction must decrease as the wavelength is reduced. Fig. 13 (full line) gives a rough indication of the upper limit of power obtainable with present day technique at wavelengths below 100 cm. It is worth noting that there is a physical as well as a technical upper limit to the power; this is reached when the necessary high frequency voltage is so great as to produce a discharge across an oscillatory circuit having the largest possible dimensions relative to the wavelength. This limit has not yet been reached, though corona discharges have been produced from micro-wave aerials with pointed ends.

To produce powers approaching the upper limit indicated in fig. 13 it is necessary to design valves for a substantially fixed wavelength and without regard to the size and power consumption of the field magnet. A large number of valves would thus be required to cover the whole waveband from about 10 cm. upwards. Commercial requirements do not

TABLE I.

	DYNATRON OSCILLATIONS.		ELECTRONIC* OSCILLATIONS
	2-segment anode.	**4-segment anode.**	
Wavelength, λ	Depends mainly on circuit dimensions		Depends mainly on magnetic field strength.
Circuit length (parallel wires)	Rather less than $\frac{\lambda}{4}$	Rather greater than $\frac{\lambda}{2}$	About $\frac{\lambda}{2}$
Min. λ (cm.)	$120 d_a^{\frac{2}{3}}$	$40 d_a^{\frac{2}{3}}$ (central fil.) $55 d_a^{\frac{2}{3}}$ (eccentric fil.)	$22 d_a^{\frac{4}{5}}$
Opt. λ (cm.)	2.5 × min. λ	Near min λ (central fil.) 2 × min. λ (eccentric fil.)	near min. λ
Max. useful λ (cm.)	5 × min. λ	4 × min. λ (eccentric fil.)	1.5 × min. λ
Magnetic field strength, H (gauss)	Adjusted to give maximum output: $\frac{\lambda E_a}{250 d_a^2}$ (opt.) †	$\frac{\lambda E_a}{125 d_a^2}$ (opt.)†	Adjusted to give required wavelength ($\lambda = \frac{12{,}000}{H}$)
Anode voltage, (V).	$1500 d_a^{\frac{2}{3}}$ (max).		$6 \times 10^5 \frac{d_a^2}{\lambda^2}$ (opt.)
Anode current (mA.)	Limited only by max. anode dissipation, or by space charge.		$4.5 \times 10^{-4} \frac{l_a}{d_a} E_a^{\frac{3}{2}}$ (opt.)
Opt. field angle (degrees)	Zero.		$7.6 \sqrt{\frac{l_a}{d_a} - 0.7} \times \left(1 - 1.8 \times 10^{-4} \frac{E_a}{d_a}\right)$
Anode gap width	about $0.1 d_a$ (opt).		up to $0.3 d_a$
Order of efficiency	40—60 per cent.	30—50 per cent.	4—8 per cent.
Wavelength range conveniently covered.	75 cm. to 10 metres.	25 cm. to 3 metres.	10 cm. to 50 c.m

d_a=anode diameter (cm). l_a=anode length (cm).

* If positively biassed end electrodes are used (voltage $\doteq 0.7 E_a$) the optimum field angle is approximately zero, the efficiency is of the order of 10 per cent, and the minimum wavelength is slightly reduced. The power dissipation is then about equally divided between anode and end electrodes. If the field angle is increased and the end electrode voltage reduced a smaller fraction of the total power loss appears in the end electrodes with little change in efficiency.

† Optimum values of field strength obtained from these expressions are liable to be too high at max. wavelength and too low at min. wavelength by a factor of about 1.5.

yet justify the development of such a range of valves. In the development of magnetron valves in the Research Laboratories the chief aim has been to provide a useful performance in the widest possible wavelength range with a small number of valves, capable of giving sufficient output to meet existing needs. Outputs obtained from some of these valves are shown by the dotted curves in fig. 13.

The Effect of Variable Loads.

There are other problems, besides the production of a large output and wide wavelength range, to be considered in magnetron design. For example, the amplitude of the oscillating anode voltage increases as the load on the oscillatory circuit is reduced. If the operating conditions are otherwise unchanged this results, in the case of dynatron oscillations, in an increase of input with a reduction of efficiency. It is, therefore, desirable to make preliminary circuit adjustments with reduced anode voltage and filament emission to avoid the risk of overloading the anode and, at wavelengths near the minimum, that of excessive electron bombardment of the filament. There also is an increasing tendency at the longer wavelengths for electrons to escape from within the anode under conditions of light load. Bombardment by these electrons may lead to serious local heating of the anode supports and, in some cases, of the glass bulb. It has been found impracticable to prevent the escape of electrons from the anode by structural alterations without increasing the inter-electrode capacitance to a serious extent. On the other hand if the input rating is reduced to the point at which no maladjustment can possibly cause an overload the output of the valve will, as with most transmitting valves, only be a small fraction of the maximum power it can safely give with proper adjustment. Two devices have been developed to overcome these difficulties in such cases as electro-medical applications where the load is of an essentially variable nature. These are : (1) the use of specially designed shields to minimize bombardment of the anode supports and the bulb, and (2) an automatic control circuit which holds the valve input at a low value until the load on the circuit is sufficient to enable the valve to handle its maximum input with safety. In cases where the load is approximately constant proper initial adjustment is all that is required.

Modulation.

For radio transmission purposes the output of the oscillator must be modulated, and for telephone or television signals the modulation must be linear. At long wavelengths this can only be satisfactorily achieved, in the valve itself, by varying anode voltage and magnetic field strength together. The modulation of the field current presents considerable difficulties both with respect to frequency characteristic and power consumption. At ultra-short wavelengths, however, useful if not perfect modulation characteristics can be obtained by more readily

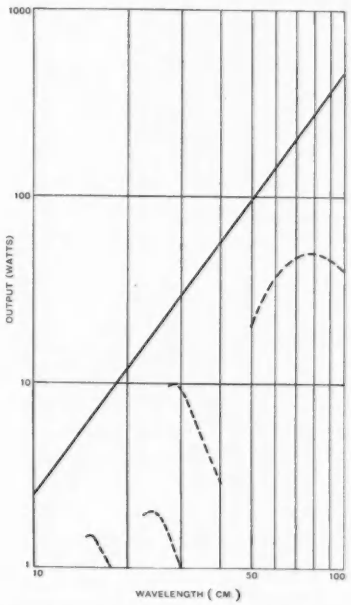


Fig. 13.—Approximate upper limit of output (full line) and typical output from valves designed to cover a wide wavelength range (dotted curves).

practicable methods. For dynatron oscillations anode voltage modulation can be used provided the wavelength is not too far above the minimum or, what comes to the same thing, the anode voltage is not too high. A preferable method is to apply the modulating voltage to a grid of the type already described (fig. 12). The grid is biassed negatively and its potential rises to approximately zero on the modulation peaks. It is important that the grid

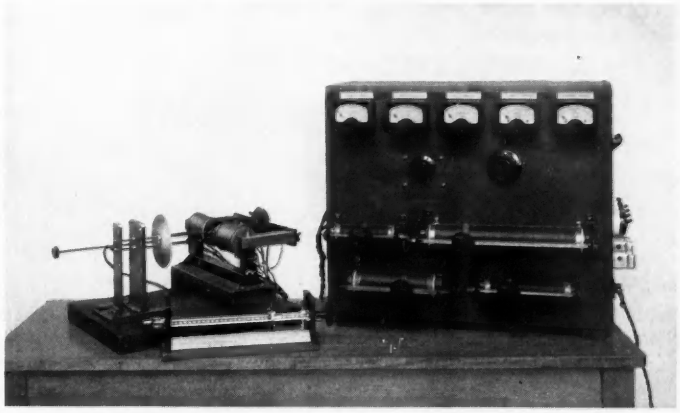


Fig. 14.—Magnetron oscillator with power supply unit and absorption wavemeter. The oscillator parallel wire system shown is for $\lambda = 20$ to 35 cm. and is interchangeable with other systems for longer wavelengths.

should not swing far positive or it may take a heavy current and be burnt out. This method as well as giving better modulation characteristics has the advantage of requiring a very small modulating power. The possible modulation depth and the optimum bias both increase as the wavelength is reduced; they are of the order of 30 to 60 per cent

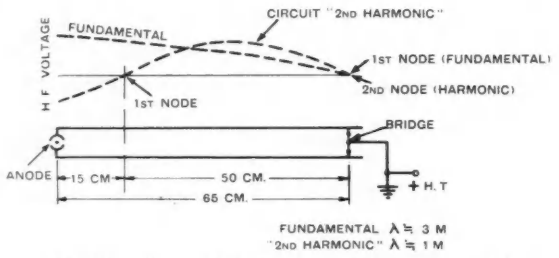


Fig. 15.—Illustrating fundamental and harmonic resonance in a parallel wire oscillatory circuit.

and −100 to −300 V. respectively for a CW11 valve (see below) at wavelengths of 3 metres to 1 metre. The frequency modulation may be of the order of 2 per cent when no special precautions are taken to reduce it. It can, however, be considerably reduced by using an oscillatory circuit with large

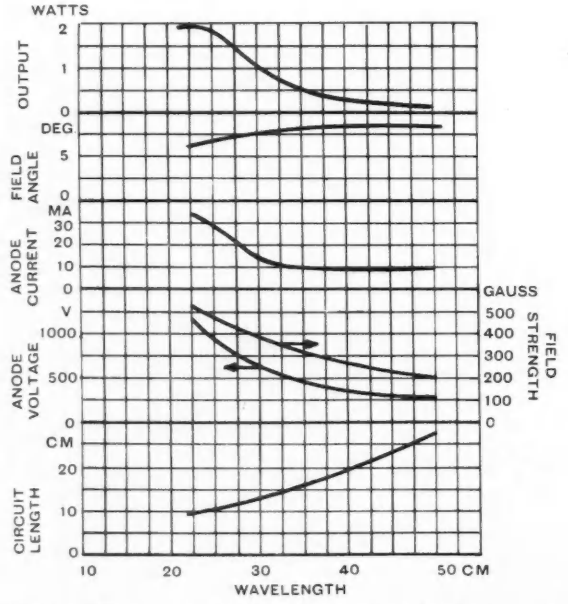


Fig. 16.—Typical operating characteristics for electronic oscillations; valve type CW.10. The filament voltage must be adjusted to give the proper value of anode current shown above.

capacitance—concentrated or, preferably, distributed—and also by modulating grid and anode voltages together. Simple grid modulation with ordinary parallel wire oscillatory circuits has, however, given satisfactory results in radio transmission tests. For electronic oscillations anode voltage modulation gives good linearity up to 50 per cent or more with about 0.5 per cent frequency modulation. The adjustment of the field angle is important.

The difficulty of reducing frequency modulation to a negligible amount at ultra-short wavelengths, when the modulation is carried out in the oscillator valve, has led to the study of absorption methods acting either on the oscillatory circuits or on the emitted radiation. While some of these show considerable promise they are not free from disadvantages and the most satisfactory solution may prove to consist in making use of the frequency modulation instead of suppressing it, the amplitude being held constant. The whole problem of modulation is, however, still under active consideration. For radio transmission and similar purposes, the supplies to valve and magnet should be smooth D.C. For other purposes A.C. filament heating and unsmoothed rectified supply for the magnet may be used.

Oscillating Circuits.

The most convenient type of oscillatory circuit for general use consists of a pair of parallel conductors tuned by a sliding bridge, to the centre of

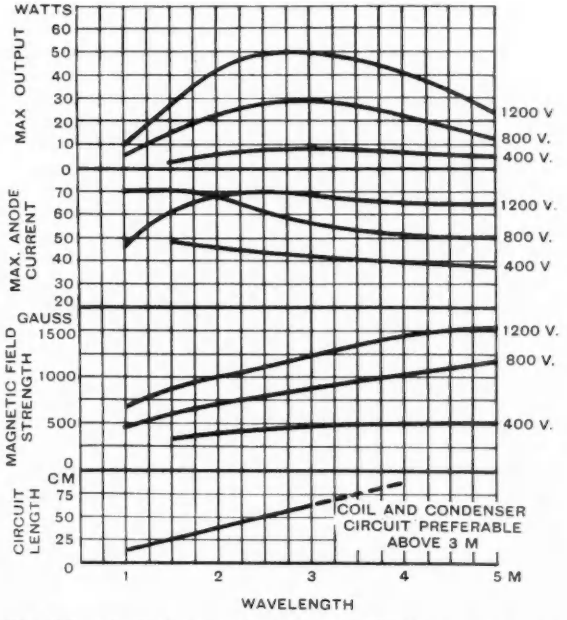


Fig. 17.—Typical operating characteristics for dynatron oscillations; valve type CW.11. For wavelengths near the minimum the filament voltage must be reduced so that the anode current does not exceed the values given above.

which the positive H.T. connection is made (fig. 15). It is often desirable to earth this lead rather than the negative, so that only radio frequency potentials are present on the circuit. The spacing between the conductors, which may conveniently consist of $\frac{3}{16}$ inch or $\frac{1}{4}$ inch brass rod or tube, should not exceed 1/10 wavelength. The radiation loss is

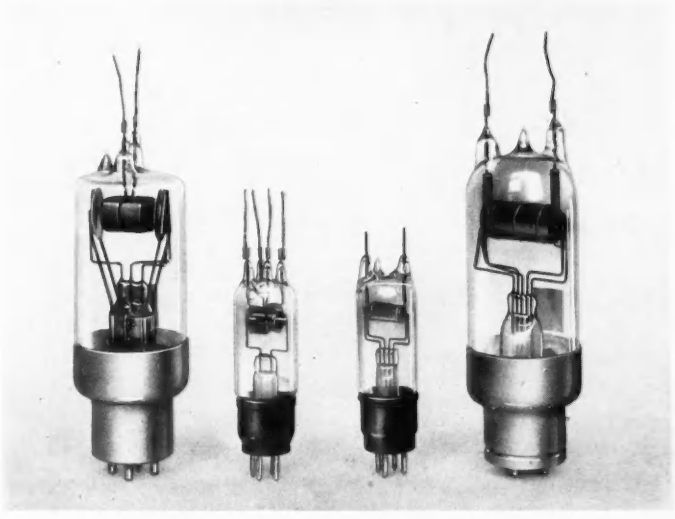
negligible for spacings less than 1/30 wavelength but as this is mechanically inconvenient for the shortest wavelengths the bridge should then take the form of a metal disc whose diameter can with advantage be up to one wavelength if the spacing is 1/10 wavelength or more (fig. 14). The circuit lengths referred to in Table 1 and figs. 16 and 17 (below) are to be measured from the bridge to the anode. When used for wavelengths above the optimum this type of circuit may tend to oscillate in a harmonic mode instead of at the desired wavelength, owing to the lower valve impedance at shorter wavelengths. This is illustrated in fig. 15. For relatively long wavelengths, a coil and condenser circuit with a rather large L/C ratio is therefore preferable.

Valve Data.

Figs. 16 and 17 show typical operating characteristics for electronic and dynatron oscillations respectively.

Data for the magnetron valves which have been developed in the Laboratories for commercial use, or are in development with a view to such use, are given briefly below.

TYPE CW. 10 (fig. 16). General purpose valve for 22–35 cm. (electronic oscillations, 2 watts max. output) and 1.2–5 meters (dynatron oscillations, 30 watts max. output). Filament 3.7 V. 3.8 A. for 80 mA. emission. Max. anode voltage 1000–1200 V. Anode dissipation 40–50 watts. Magnetic field 250 to 1250 gauss; air gap 1½ inches.



(a) (b) (c) (d)

Fig. 18.—Typical magnetron valves.

(a) Experimental valve; 10 W. output at 25–30 cm.
(b) Type E.639.
(c) Type CW.11.
(d) Type E.465.

Harmonic resonance of the circuit is, however, useful for dynatron oscillations of wavelength less than about 1 metre, *i.e.* particularly for 4-segment valves. The first node then occurs close to the anode seals and if the bridge is placed there efficient coupling to the load is difficult. If the bridge is moved one half-wavelength further from the valve this difficulty is obviated. For electronic oscillations the effective valve impedance is very low (of the order of 10–100 ohms) and resonance occurs when the circuit length is an integral number of half-wavelengths.

Coupling to the load through a matched transmission line is desirable for most practical purposes. In the case of a concentric line the outer should be connected directly to the bridge.

TYPE CW. 11. (Fig. 17). Fitted with grid for dynatron oscillations at 1–5 metres (50 watts. max. output). Not suitable for use as an electronic oscillator. Filament 3.7 V., 3.8 A. for 80 mA. emission. Max. anode voltage 1200 V. Anode dissipation 50 watts. Grid bias for maximum output approximately zero. Magnetic field 500–1500 gauss; air gap 1½ inches.

TYPE E. 639. Valve with 4 anode segments allowing either "4-segment" or "2-segment" connection to the circuit to give alternative wavelength ranges of 0.5 to 1.5 metres (output 20–40 watts), and 1.5 to 5.0 metres (output 20–50 watts). Filament 3.7 V., 3.8 A. max. Anode voltage 1000–1500 V. Anode dissipation 60 watts. Magnetic field 500–1500 gauss; air gap 1½ inches.

TYPE E. 465. Suitable for use under conditions of variable load (electro-medical) as well as for radio purposes. Fitted with grid to be connected directly to filament except when used to control or modulate the output. Wavelength range 2 to 8 metres (150 watts max. output). Filament 5.5 V., 6.5 A. for 200 mA. emission. Max. anode voltage 2000 V. Anode dissipation 150 watts. Magnetic field 400–1000 gauss; air gap $2\frac{3}{4}$ inches.

FIELD MAGNETS.

Design.

The substitution of properly designed iron-cored field magnets for the uneconomical solenoids used in the early experiments has been an important factor in the development of the magnetron oscillator. The chief principles in design are, first, that the iron cross-section should be large enough to avoid serious saturation in the working region and, in addition,

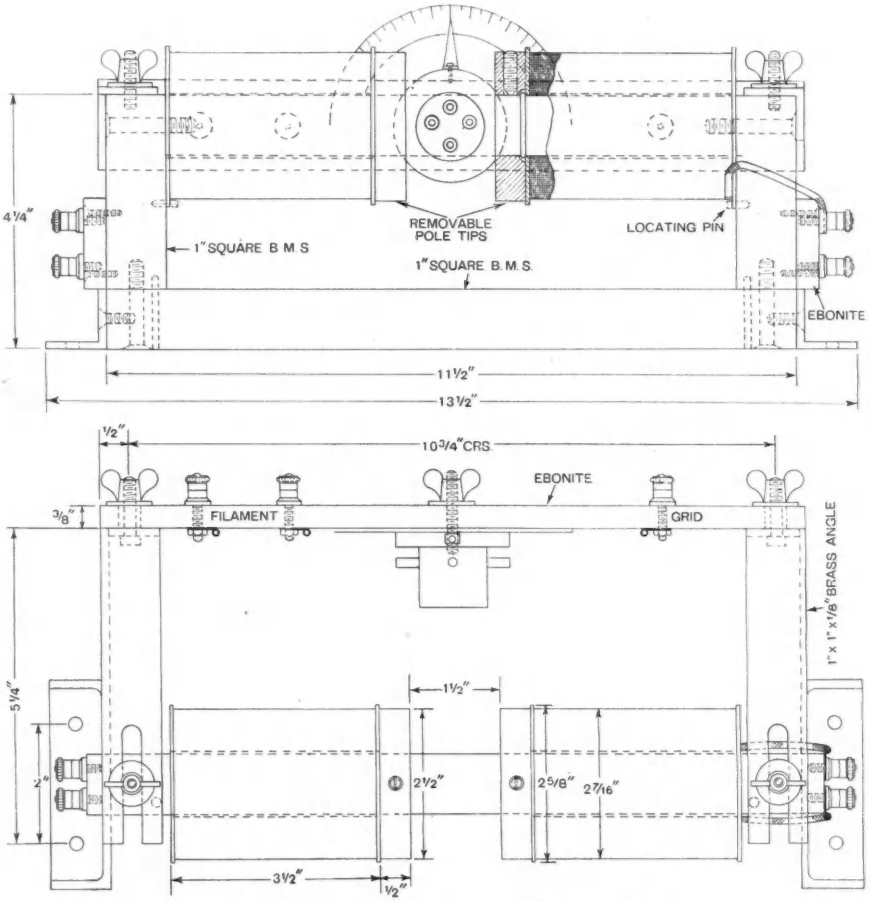


Fig. 19.—Electro-magnet and valve mounting.

The anode diameters of these valves, for use with Table 1, are approximately as follows:—CW.10., CW.11. and E.639 – 1 cm.; E.465 – 2 c.m.

Among other valves developed for experimental purposes may be mentioned one giving a continuous output from about 10 cm. upwards, sufficient for certain physical measurements such as absorption in ionized gases, and another giving an output of about 10 watts at wavelengths of 25–30 cm.

Examples of several of the types mentioned above are shown in fig. 18.

that

d_p = at least 2 d_a for dynatron oscillations

and d_p = at least 4 d_a for electronic oscillations,

a more uniform field being required for maximum efficiency in the latter case. d_p and d_a are the pole and anode diameters respectively. The last condition (for electronic oscillations) is often inconvenient and can be replaced by making d_p at least 2 d_a and fitting cylindrical pole tips of diameter about 6 d_a and length about d_a. The length of the iron circuit is relatively unimportant on account of the large

air gap and little is gained by the use of special soft irons; ordinary mild steel is quite satisfactory. It has also been found that no practical advantage can be obtained by using specially shaped poles instead of cylindrical poles with flat ends.

Typical Magnet Systems.

Fig. 19 shows the arrangement of the standard magnet and valve mounting for use with the CW. 10, CW. 11 and E. 639 valves. The mounting allows a slight movement of the valve in any direction to ensure proper alignment in the field. The approximate relation between current and field strength for this magnet (coils in series) is given below :—

Field Current (A) ..	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Field Strength Gauss (1 inch poles)	230	420	610	800	970	1130	1280	1400	1520
Ditto :— (With 2½ inch pole tips)	220	400	540	650					

For continuous operation the field current should not exceed 3.5 A. Each coil is wound with 800 turns of 18 S.W.G. enamelled wire (resistance about 2 ohms). The weight of the complete unit is about 15 lbs.

A similar magnet for use with the E. 465 valve has 1½ inch poles, 2¾ inch air gap, and coils 5 inches long with 1500 turns of 18 S.W.G. enamelled wire (about 10 ohms) each. A current of about 3 A. is required for a field strength of 900 gauss.

In designing these magnets a compromise has been effected between power consumption and weight such that the overall efficiency of the oscillator is not seriously reduced while the weight does not preclude their use in mobile equipment.

With the magnet steels now available permanent magnets are quite practicable, particularly for low power sets. For electronic oscillations they greatly simplify the problem of maintaining a constant frequency. Fig. 20 shows a permanent magnet with

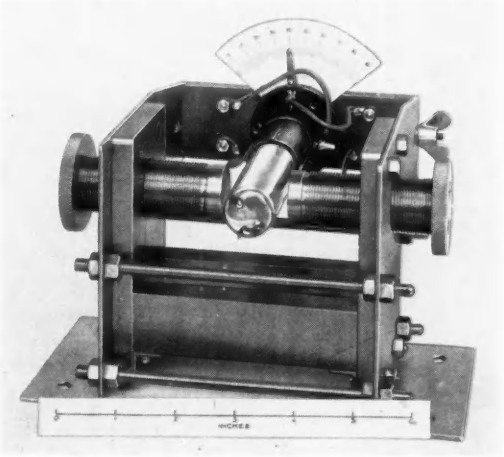


Fig. 20.—Experimental adjustable permanent magnet.

variable air gap, giving a field strength range of about 250 to 550 gauss with a minimum gap of 1 inch, designed for use in an experimental magnetron receiver. It has been found possible to obtain an audible beat note between two oscillators using such magnets at frequencies over 1,000 megacycles.

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The Testing of Large Alternating Current Circuit Breakers.

PART II.—GENERAL DESCRIPTION OF THE HIGH POWER TEST LABORATORY AT WITTON.

By W. WILSON, D.Sc., B.Eng., M.I.E.E.
Development Department, Witton Engineering Works.

GENERAL SCHEME.

AS stated at the end of Part I.[1] of this series of articles, the High Power Test Laboratory at Witton is designed to produce an instantaneous three phase short circuit of up to two million kVA, capable of testing circuit breakers rated up to one and a half million kVA at voltages ranging from 6.6 kV to 132 kV. Lower capacities can be obtained at voltages down to 400 and 230 by means of field regulation or a step-down transformer. These provisions cover all the standard requirements of power supply today, but the laboratory is laid out in such a way as to facilitate any future extensions that may be necessary, for example, as regards short circuit capacity, voltage, or volume of work.

The chief requirements that were borne in mind, namely, safety, reliability and economy of time, were facilitated by the adoption of a straightforward arrangement in which the various constituent parts are located in logical succession. In this way each part is readily afforded its correct treatment, while at the same time the lengths of leads and connections are kept to a minimum. It was found possible in practice to adopt a straight line arrangement both of plant and buildings, without involving any waste of floor space.

Safety has been ensured for the personnel by housing the various units in three buildings, namely the generating station, the test bay and the observation room. Only the observation room is occupied during an actual test, and it is situated thirty yards away from the test bay which is built on to the end of the station. The single line diagram in fig. 19 and the plan layout of fig. 20 show the order of the constituent parts in the combined building, and illustrate what has already been stated in regard to the logical and straight line arrangement of the components.

1. "G.E.C. Journal" Vol. VII., No. 1., p.65.

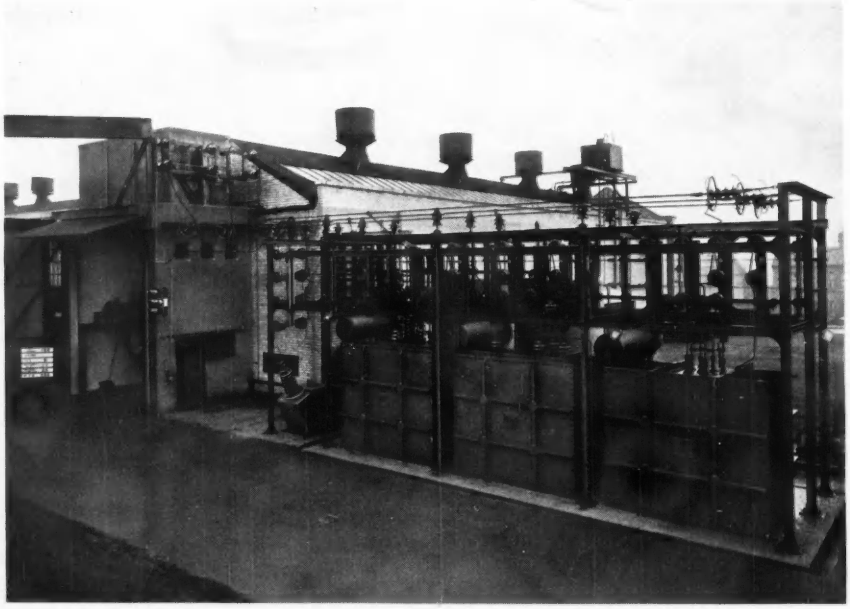

Fig. 18.—View of the High Power Test Laboratory at Witton Engineering Works, seen from the test bay end. In the foreground are the step-up transformers. The observation building is not shown in this view.

From the point of view of the safety of the plant, it will be appreciated that the alternator must be provided with special safeguards, as it forms the most costly item as well as being the most difficult to repair in the event of damage. The most likely sources of trouble are, first, the master circuit breaker, and secondly, the reactors and their connections. A partition interposed between the alternator and the breaker would have been a

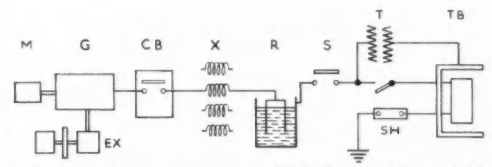

Fig. 19.—Diagrammatic arrangement of the testing plant.

serious hindrance, and would still have left unprotected the plant on the open side, as well as the building itself. The master-breaker has therefore been enclosed in a strong ferro-concrete cubicle, and since the reactors are sufficiently remote from the machines to prevent damage spreading from one to the other, a safe arrangement has been achieved without impairing access and supervision.

The main classes of apparatus comprise (1) generating equipment of the necessary large short circuit capacity, including transformers for giving the various voltages; (2) external reactance and resistance for regulating the magnitude, and if desired the power factor, of the short circuit; (3) separate switches for throwing on the short circuit and for removing it an instant later if the test switch has not already done so; and (4) recording apparatus, chiefly concentrated in the observation building.

The fundamental test requirements are high power and low inherent impedance. The latter, which consists almost entirely of leakage reactance, has been minimized by the adoption of those features of design that reduce flux leakage. Great mechanical strength is also a feature of the equipment. Details of the methods whereby this and the other necessary qualities have been secured are given in the following sections which describe the various components.

GENERATING PLANT.

The alternator (seen on the right in fig. 21 and in fig. 33) is arranged to give four voltages by the series-parallel connection of its double winding, and by star or delta connection at the terminals. These changes are quickly accomplished by means of isolating switches. The voltages obtainable are 6.6, 11, 13 and 22 kV.

The normal output at full voltage is 2 million kVA on open circuit voltage and symmetrical current. By applying the maximum field boost, the instantaneous output is increased to 2.8 million kVA. If the asymmetrical values of current are taken into consideration these values are increased to 2.8 and 4.0 million kVA respectively.

A full description of the alternator, driving motor, exciter and auxiliary equipment is given in Part III. of this article, which appears on page 115 of this issue.

BUS BARS.

The chief requirements that were borne in mind in the design of leads and connections were accessibility, rigidity and low capacitance. All these were met by making the bus bars of 3 in. copper tubing, having an area of 3 sq. ins., and supported overhead in air at 5 ft. centres. The advantages of tubular bars as regards low skin and proximity effects and mechanical strength are well known, and since they are of standard design for metalclad switchgear, all the necessary joint and connection fittings were readily available.

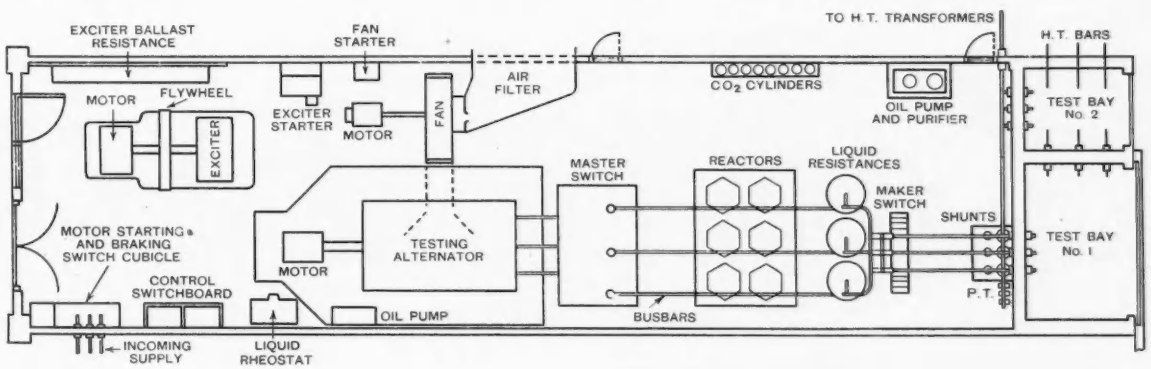

Fig. 20.—Plan of the generating station and test bays showing the disposition of the testing plant. Note the straight line arrangement of the components.

A maximum force slightly under one ton per foot may be produced between the bars by the short circuit current, increasing to about two tons per foot where the bars approach each other near the alternator terminals and the maker switch. Special supports were accordingly designed to withstand these stresses.

MASTER SWITCH.

Separate switches are installed for throwing on the short circuit, and for clearing it if the test breaker should fail to do so. The former function is carried out by a maker switch located just before the test bay, while the latter is fulfilled by a standard 1,500 mVA oil circuit breaker, housed in the ferro-concrete enclosure. The breaker has already been fully tested for rupturing capacity; but as it will be required to back-up test breakers of its own rating, a margin is desirable. This is provided by the practice of interrupting the field of the alternator before the breaker is opened.

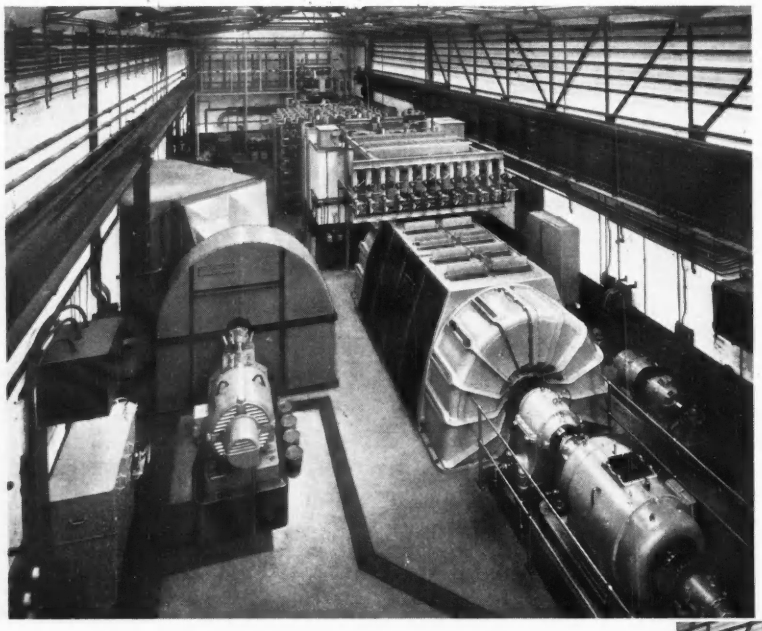

Fig. 21.—The generating station of the High Power Test Laboratory looking towards the test bay, showing the test alternator on the right and the air cooling fan on the left.

REACTORS.

The magnitude of the short circuit that is applied at a given voltage is regulated by the amount of reactance. A certain minimum quantity must always be present, namely, the 2.6 per cent (0.27 ohm at 22 kV) of the alternator. For tests at higher voltages, the reactance of the step-up transformer will have to be added, an amount which is actually almost equal to that of the generator. For the great majority of tests, requiring less than the maximum possible short circuit capacity, further reactance is inserted to limit the current to the desired value.

Four centre-tapped concrete type reactors are installed in each phase, as shown in fig. 23. They are mounted two high, and the sections are interconnected by means of self-latching isolating switches. Only a few minutes are thus needed to make any desired connection. A total of 37 different combinations is available, affording a similar number of reactance steps.

Since the main current passes through the reactors and their connections, there is the same need for rigidity and strength of the reactor supports as for the bus bars. The methods whereby these characteristics have been obtained can be seen in fig. 23.

RESISTORS.

There is ordinarily no need to insert resistance in the test circuit; for the most severe short circuits that occur in practice pass through very little impedance other than the reactance of the machines and transformers, and testing procedure simulates this condition. The addition of small values of resistance increases the power factor, but produces an almost negligible effect upon the magnitude of the current.

It should be appreciated that the greater the angle of lag, the more difficult is the process of arc extinction, and specifications therefore lay down that the power factor must not exceed a given value, such as 0.15 or 0.3. Investigations have shown that the severity of the test does not change by more than about 10 per cent for power factors below 0.3.

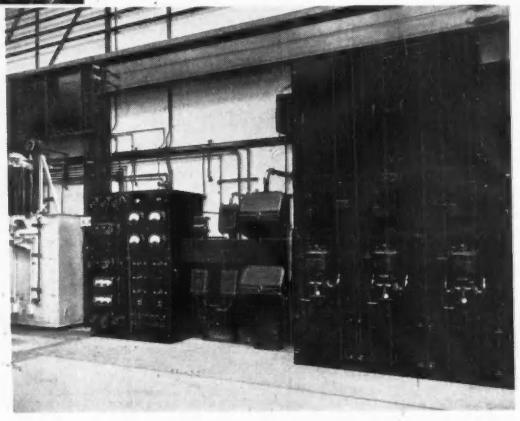

Fig. 22.—Motor starting and braking switch cubicles in the generating station. To the left is the control switchboard.

The value that is usually obtained during tests at the laboratory is approximately 0.05, since it is not considered desirable to bring this to the most favourable figure permitted by adding resistance.

In case it should be rendered necessary to modify the power factor to comply with specified conditions, or for the purposes of a special investigation, a liquid rheostat is inserted in each phase capable of passing the required currents and providing the desired resistance range. It has been designed so that the whole of the liquid is uniformly heated by the current, and is provided with compressed air agitation for quickly mixing the electrolyte. The rapid discharge of the liquid is also effected by air pressure.

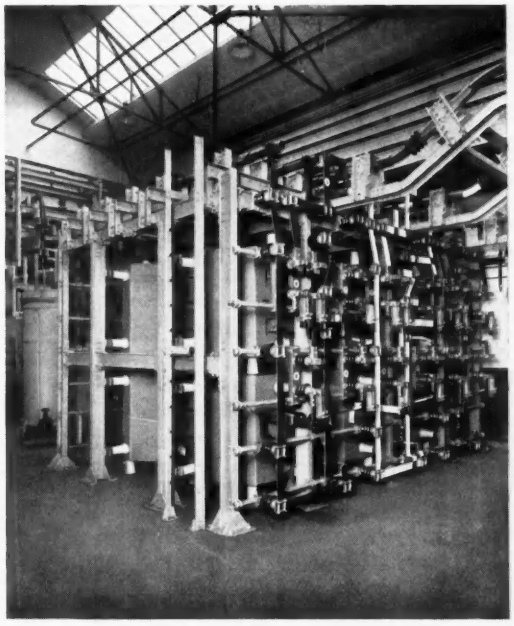

Fig. 23.—View of reactors, showing one of the banks of heavy current isolating switches for varying the reactance in circuit. On the left is seen one of the resistance tanks.

MAKER SWITCH.

When tests for breaking capacity only are being made, the test switch is initially closed, and it is short circuited across the bus bars by means of the maker switch, fig. 24. This switch is never required to break any current and is therefore designed to operate in air, the absence of oil minimizing the erosive effect of any arcing that may take place on making the circuit.

There are two breaks per phase, the moving contact falling vertically to close under the influence of a spring, and being opened by a solenoid. The forces due to the short circuit are in such a direction as to press the contacts into engagement.

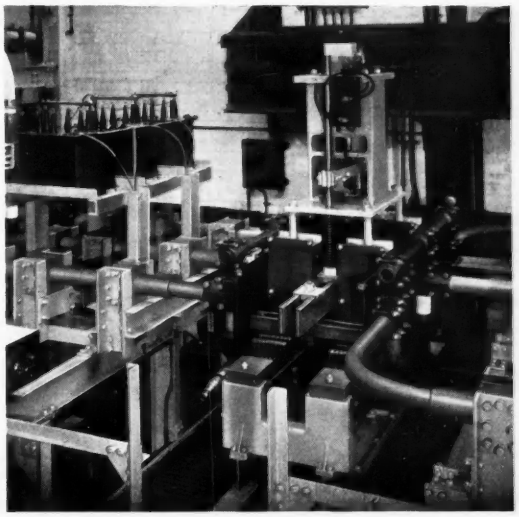

Fig. 24.—Maker switch (shown in open position). This view also shows the method employed for mounting the 3-inch diameter tubular bus bars.

POWER TRANSFORMERS.

Tests at above 22 kV and below about 5 kV will be effected through the medium of step-up or step-down transformers. The largest are the set of three by which the voltage is raised for tests on breakers of up to 132 kV. They have a normal rating of 50,000 kVA, and it has been found possible to design them with a reactance of only 2.53 per cent. Interleaving and close spacing of the windings were necessary to produce so low a figure. The forces on the end turns during a short circuit test amount to as much as 500 tons, necessitating special attention to the mechanical design. The units are of the outdoor type, and have no special provision for cooling since they do not have to pass current for more than a fraction of a second at a time. A steel framework is mounted over them for carrying the connections and the various items of outdoor switchgear. This is shown in fig. 18.

The step-down transformer consists of a single three phase unit with its secondary windings sub-divided into four sections. Thus a complete range of voltages can be obtained by series-parallel and star-delta interconnection providing pressures down to 400 and 230 volts. Breaking capacities available at certain typical voltages are given in the following table :—

Voltage.	Breaking Capacity.
	Amps.
3800	30,000
2200	52,000
1100	104,000
550	208,000

Further details of the transformers and reactors will be given in Part IV. of this article.

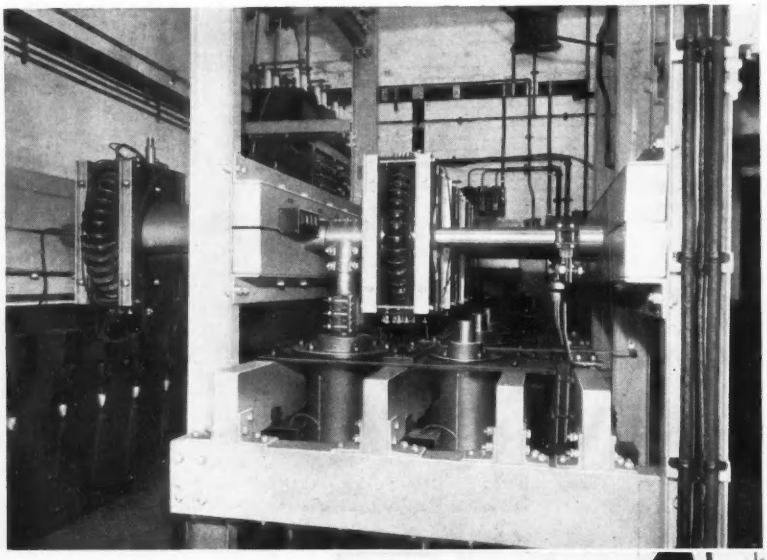

Fig. 25.—Shunts and instrument transformers for operating the oscillographs and protective gear respectively. The shunts of largest capacity are shown connected up.

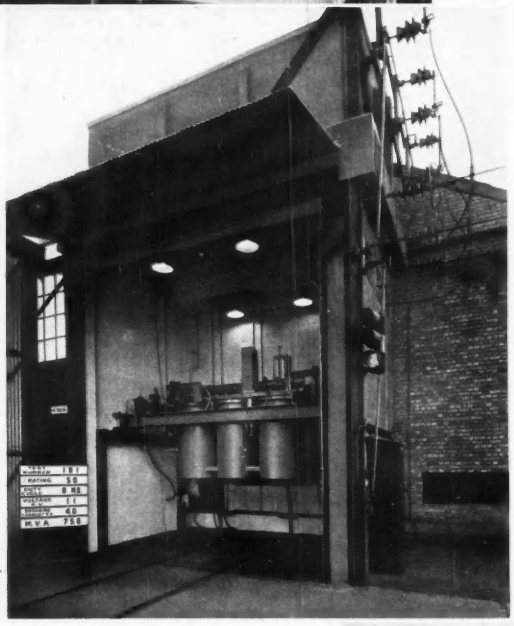

Fig. 26.—Test bay showing a 1,500,000 kVA oil circuit breaker mounted ready for testing.

COUPLINGS FOR INSTRUMENTS.

The bus bars pass from the station into the test bay, where they are connected to the incoming terminals of the breaker undergoing test. The corresponding outgoing terminals are led to three lower bars passing back into the station, where they are connected to one another and to the earth bar. The shunts for operating the current elements of the oscillographs and the current transformers for the wattmeter elements are inserted immediately before the earthing point, and the connections are taken off for the resistance potential dividers and potential transformers for the potential elements and voltmeters.

All these components will be described in detail in Part V. of this article, which will deal with the instrument equipment of the laboratory.

TEST BAY.

The test bay, fig. 26, is a ferro-concrete chamber built on to the end wall of the main building, and open towards the observation house. The test bay can be completely closed by a sliding door operated electrically and controlled by a push-button at the observation desk in the observation house. When the door is closed, the atmosphere in the enclosure is sealed, and any conflagration can be immediately extinguished by means of either the carbon dioxide equipment or the Mulsifyre apparatus with which it is fitted.

A 10-ton electric hoist is provided in the test bay and enables the test switches to be placed in position, and their tanks rapidly raised or lowered for inspecting the contacts.

In order to improve the load factor of the plant, a second test bay is to be erected in the empty space to the right of the existing bay. This will be of somewhat smaller dimensions, and is intended to deal especially with apparatus having breaking capacities not exceeding 500,000 kVA.

OBSERVATION HOUSE.

The building from which the behaviour of the test switch is observed is situated on the hill behind the station, where the best possible view can be obtained through observation slits without danger to the observers. The building is shown in fig. 27. The main control desk, forming the nerve centre of the whole scheme, is located at the principal slit; while the same building houses the remote

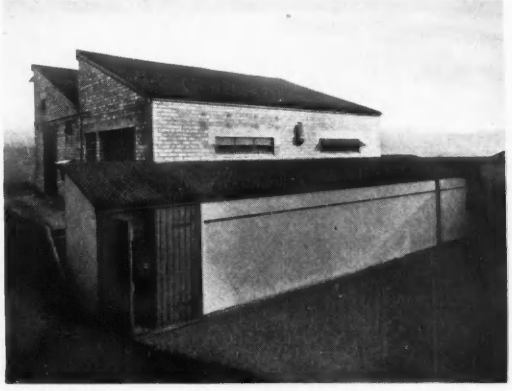

Fig. 27.—Exterior of the observation house and control building. The observation slots are clearly seen in the front wall of both buildings.

control gear for the machinery in the station, together with the apparatus for initiating the short circuit and the instruments for recording in every detail the results of the test.

Immediately in front of the observation room is situated a long gallery, provided with viewing slits throughout its length, and capable of accommodating up to 50 observers. This room is comfortably fitted out, and serves also as a conference room for visiting engineers, and as a typists' and computers' office during ordinary testing times.

The instrument equipment is naturally of an elaborate nature. It will merely be summarized in this article, and a full description will appear in Part V. of this article.

Initiation of a short circuit test is carried out by means of a pendulum, which can be adjusted to swing at a wide range of speeds, and which is automatically released after the pressing of the firing button. In the course of its travel, it trips a series of up to 12 contacts, each of which carries out a separate function at exactly the right instant. The following is a typical set of operations, effected by means of six successive contacts :—

(1) Disconnect motors driving alternator and exciter (by means of firing button); (2) open oscillograph shutter and boost lamp voltage; (3) boost excitation; (4) close maker switch, applying short circuit; (5) trip test switch; (6) trip alternator field switch; (7) trip master switch.

This routine may be varied in a number of ways which need not be described here. For example, the tripping of the circuit breaker may be arranged to take place considerably before the short circuit is applied, in order to secure interruption before the current has had time to fall to any great extent.

The most important records are taken by means of a 12-element electro-magnetic oscillograph, which, like the pendulum, was designed and made in the Development Laboratory. All the indications are recorded on the one film, a policy

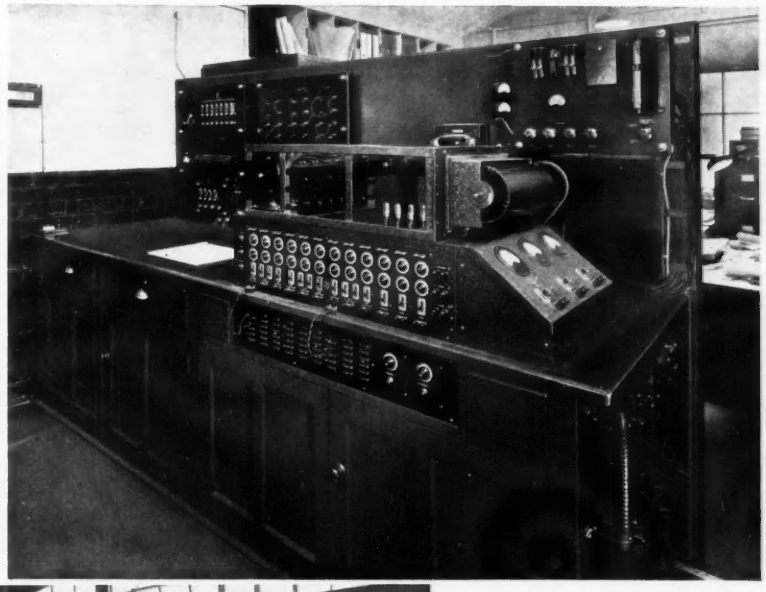

Fig. 29 (left).—The main control board in the observation house.

Fig. 30 (above).—12-element electro-magnetic oscillograph in the observation house.

Fig. 28.—Control room in the observation house showing the pendulum which initiates the short circuit test. On the right is the firing board.

which makes for simplification, certainty, and reduction of labour. Gasfilled projector lamps are used, which relieve the attendant of all worry as regards focussing, trimming, and continuity. The use of so many elements enables numerous measurements to be made, such as the current, voltage, and arc energy in each phase, current in trip coil, exciting current, oil pressure, and contact travel. The last determination is also made mechanically by means of a large kymograph mounted in the test bay.

A specially interesting feature is the cathode ray oscillograph, the purpose of which is to record the fluctuations of voltage that take place at the instant of arc rupture. It is now recognized that the question whether a given breaker will interrupt the circuit or not at any particular current zero depends on the relative steepness of the restriking voltage wave. Since this wave is part of a high frequency vibration, at the natural frequency of the circuit itself (which may be anything up to 100,000 cycles per second), it is far beyond the capabilities of the electro-magnetic oscillograph, and the cathode ray instrument, with its negligible inertia, must be employed.

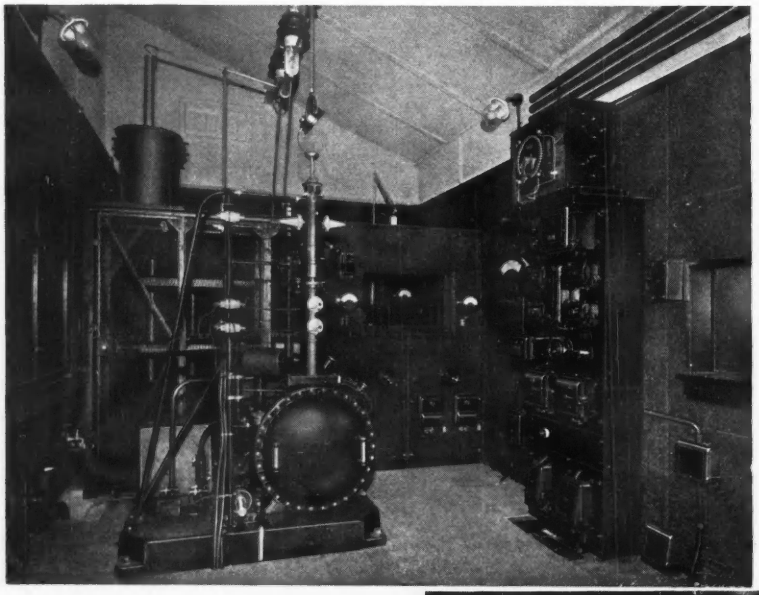

Fig. 31.—Cathode ray oscillograph room in the observation house. On the right is the L.V. control panel, and at the back the H.V. control board.

The cathode oscillograph which is installed in the largest of the rooms in the observation building is a most effective instrument. It is about eight feet high, and records upon a photographic film fixed to the periphery of a drum of over two feet in diameter, rotating at a film speed of four miles a minute. This drum is actually located in the high vacuum of the oscillograph, and it is therefore necessary to create this vacuum every time the film is changed. The pumping system, consisting of mercury vapour units backed by rotary box-pumps, has been so organized that only twenty minutes are required for film-changing and evacuation.

A darkroom, fully equipped for high speed working, is situated between the two oscillograph rooms, with traps to enable films to be passed in from both instruments. The oscillograms are developed immediately they are delivered, and the results available for inspection and measurement within ten minutes of the shot.

PROTECTION.

All the equipment involved in the power network is fully safeguarded by means of McColl fault protective gear, with auxiliary overload relays. Protection against fire is afforded by a very complete installation of carbon dioxide apparatus, consisting chiefly of a battery of 10 cylinders in the machine room (fig. 39, p. 119). This can be used, first, for automatically filling the casing of the alternator in the event of the protective gear registering a fault,

Fig. 32.—Photographic dark room in the observation house.

secondly, for flooding the master switch cubicle should the master breaker fail to clear a short circuit, and thirdly, for extinguishing a fire in the test bay. In addition, there is a portable carbon dioxide apparatus of two cylinders which can be used for putting out small oil or other fires in the vicinity of the test bay. A further protection is provided for the test bay in the form of a complete Mulsifyre installation, while portable Pyrene and Foamite extinguishers are located at a number of strategic points. Sand buckets are also stationed both inside and outside the buildings.

PART III.—THE ALTERNATOR AND ITS AUXILIARY EQUIPMENT.

By M. KAHN, D.Eng., M.I.E.E.
Chief Engineer, Engineering Dept., Witton Works.

THE testing of large A.C. circuit breakers has always presented many difficulties, the chief of which has been the provision of the enormous amount of electrical energy required. Circuit breakers of this type are installed in a power system to provide protection against the effects of a short circuit, which is one of the two or three major troubles that can befall electrical equipment. To be effective, a test on a circuit breaker must reproduce this major type of fault which, if not checked immediately, might lead to disaster.

In many cases the switches being tested are eventually installed where they may be called upon to clear a short circuit into which the entire energy of several large power stations is being directed. A similar condition must therefore be reproduced during the test, necessitating the installation of a generator which, momentarily at least, must give an output equivalent to that of a large power system.

This effect can be obtained from a single generator by the provision of a large machine, associated with auxiliary equipment, both of special design. In the new High Power Test Laboratory at Witton the generating plant comprises an alternator running at 3,000 r.p.m. of a particularly interesting design, driven by a comparatively small motor. Excitation is supplied by an exceptionally large motor-generator flywheel set, capable of giving a considerable boost at the moment of short circuit. Both alternator and motor are cooled by air supplied from a separate fan, while a system of lubrication is installed which not only ensures a constant supply of oil to the bearings, but enables the initial friction of the alternator and exciter bearings due to the heavy weight of the alternator rotor and the exciter flywheel to be overcome when starting. This equipment is described in detail below.

THE ALTERNATOR.

As already stated, the alternator (fig. 33) is a 3,000 r.p.m. machine. This speed was decided upon in order to keep the physical dimensions down to a minimum and, incidentally, to reduce the overall dimensions of the foundations, which consist of a solid block of concrete 12 ft. deep, weighing 450 tons. It is of interest to note in passing that during a short circuit test a maximum force of approximately 200 tons is exerted on these foundations. A cross section of the alternator showing the alternator and its foundations is shown in fig. 34.

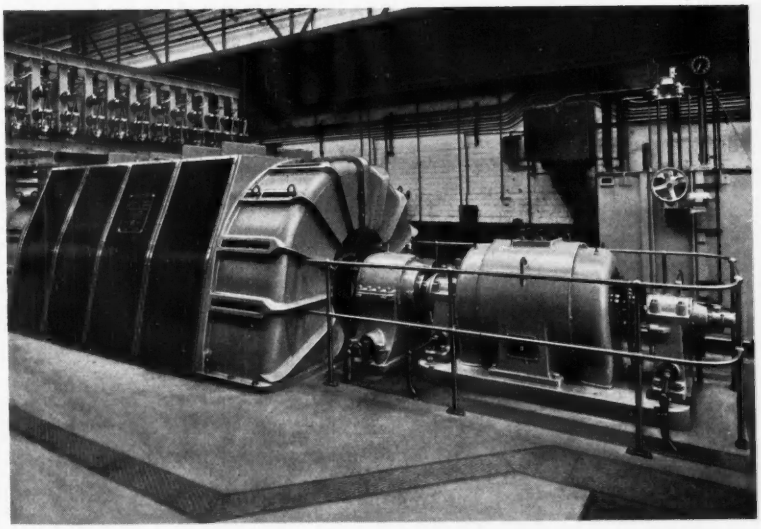

Fig. 33.—Test alternator and driving motor. Over the alternator at the far end are 12 gang-operated switches for earthing each section of the alternator stator winding.

The alternator is capable of giving four output voltages of 6.6, 11, 13 and 22 kV by different connections of the stator winding. Two maximum kVA outputs are associated with each of these voltages, namely, the normal (unboosted) output and the boosted output, depending on the amount of excitation applied during the short circuit period. Considering the 11 kV connection with the stator connected in parallel-

star, the *measured* reactance per phase (including bus bars to the test bay) is 0.07 ohms at full *normal* field current. The normal voltage at full normal field is actually 11.8 kV.

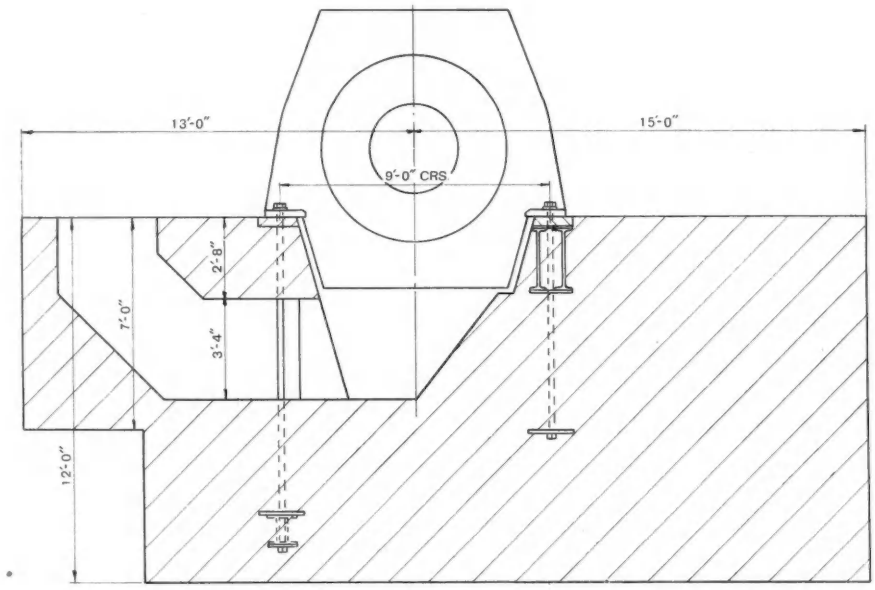

Fig. 34.—Sectional diagram of test alternator and foundations.

$$\text{Hence, current per phase} = \frac{11.8}{0.07 \times \sqrt{3}}$$
$$= 97 \text{ R.M.S. kiloamps.}$$

Therefore the normal instantaneous output during the first half cycle, calculated on open circuit voltage and R.M.S. current

$$= 97 \times 11.8 \times \sqrt{3} \times 10^3 = 2 \text{ million kVA.}$$

If the asymmetrical value of current is used (resultant of A.C. and D.C. components)[2] this value is increased to 2.8 million kVA.

By applying the maximum field boost approximately 25 cycles before the short circuit, the open circuit voltage can be increased to 14 kV.

Hence, current per phase

$$= \frac{14}{0.07 \times \sqrt{3}}$$
$$= 116 \text{ R.M.S. kiloamps.}$$

The instantaneous boosted output during the first half cycle calculated on open circuit voltage and R.M.S. current

$$= 116 \times 14 \times \sqrt{3} \times 10^3$$
$$= 2.8 \text{ million kVA.}$$

If again the asymmetrical current is taken into consideration, this value is increased to 4 million kVA.

Similar outputs at corresponding current values are obtained with each of the output voltages.

The particular characteristics required of the alternator have resulted in a design embodying a number of special features which

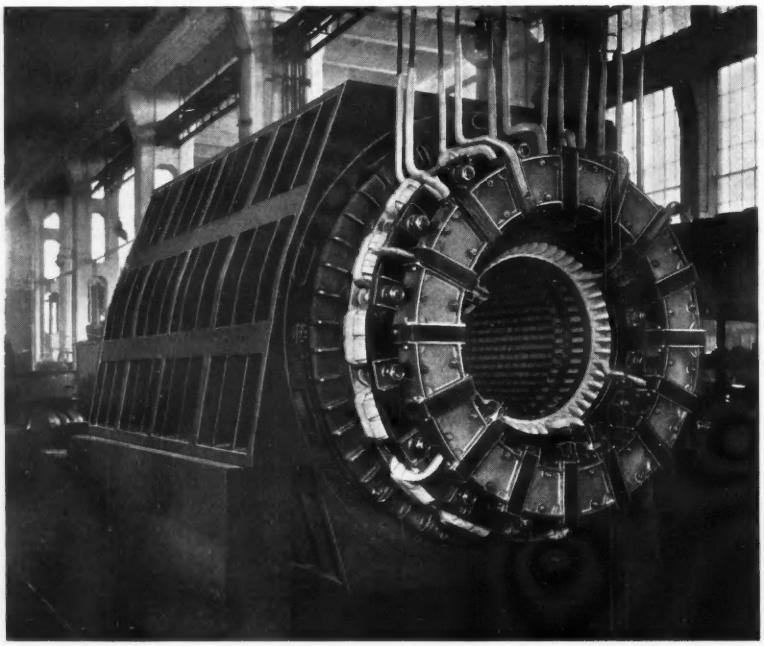

Fig. 35.—Stator of test alternator during winding, showing the reinforcing wedges and the terminals projecting from the top.

2. British Standard Specificaiton No. 116.

are quite different from those of normal high current A.C. machinery.

The stator of the machine, for instance, is of considerable interest by reason of the bracing employed or prevent displacement of the winding during a short circuit. A view of the stator during the course of winding is illustrated in fig. 35, while fig. 36 shows in diagrammatic form the method employed for bracing the end windings where they emerge from the core. This bracing is an important feature, as the points where the insulating tubes emerge are the most vulnerable during a short circuit, and special wedges (fig. 37) are inserted to support them all round the circumference. Thus, a solid ring is formed which forms a self-supporting arch, and as the side of each tube is in close contact with the supporting arch, the latter takes all the stresses which otherwise would be imparted to the tubes.

A full scale model of this assembly was tested to destruction and it was found that a pressure of 23 tons was required before the wedges started to deform. With the testing arrangements available it was impossible to break the wedges.

The end winding, as seen in fig. 36, is arranged in two tiers; it is rigidly held in position by clamping it against the face plate of the stator. The distance pieces employed for this purpose are of a bakelized material which is heat-resisting and tough, but pliable. At the same time, particular care is taken to ensure that no movement of the connections between the various parts of the stator winding can occur. The connectors are thus taken round the winding in the form of rings which are spaced by the bakelized material referred to above and held between bronze clamps. These are clearly seen in fig. 35. Similar reinforcements are employed on the connections emerging from the machine.

The end shields enclosing the stator are made of high tensile aluminium alloy similar to that used in aircraft, and embody a girder type of construction with a system of webs giving great mechanical strength. Nickel steel bolts clamp the end shields to the stator and to the floor. In order to prevent eddy currents passing from the shields to the supports, the shields and bolts are insulated.

The girder construction lends itself to the provision of a number of openings which are covered with asbestos board. This has the double advantage of reducing the eddy currents flowing in the shields and at the same time providing easy access to the machine without removing the shields.

The rotor of the alternator conforms generally to standard construction consisting of a solid forging of high grade carbon steel. As the winding of the rotor is in circuit for a short time only (although it is heavily loaded during this period) smaller slots than usual are cut in the rotor, thereby maintaining the original strength of the solid forging. A special damping winding is inserted in the slots of the rotor, above the exciting winding, to make the decrement of the short circuit current as low as possible. This damping winding also prevents an excessive rise of voltage in the rotor winding.

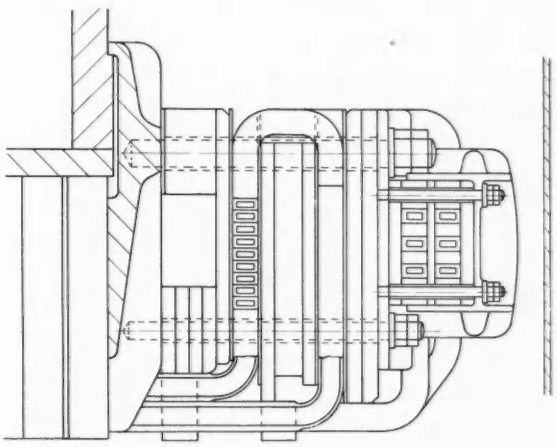

Fig. 36.—Method of bracing the end windings of the stator outside the core.

Sliprings and brushgear of large dimensions are fitted to deal with the high values of field current experienced.

DRIVING MOTOR.

The rotor is driven by a 3-phase slipring motor rated at 750 h.p.; it has an overload capacity of 1,500 h.p. and a pull-out torque of 2,500 h.p.

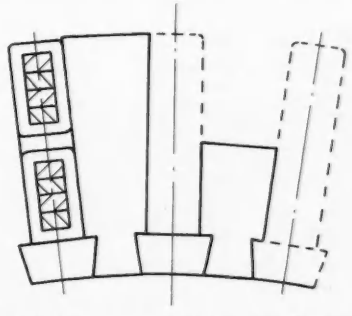

Fig. 37.—Diagram of wedges supporting the stator windings when they emerge from the core.

Since it is essential that the energy expended during a short circuit shall not cause a disturbance in the supply mains, the motor is disconnected from the supply just before the short circuit occurs. The driving motor is therefore only used to run up the alternator from rest and to supply the no-load losses of the alternator when the latter is up to its proper speed just before the short circuit is applied. As the motor is disconnected from the supply during the actual short circuit period, the whole of the

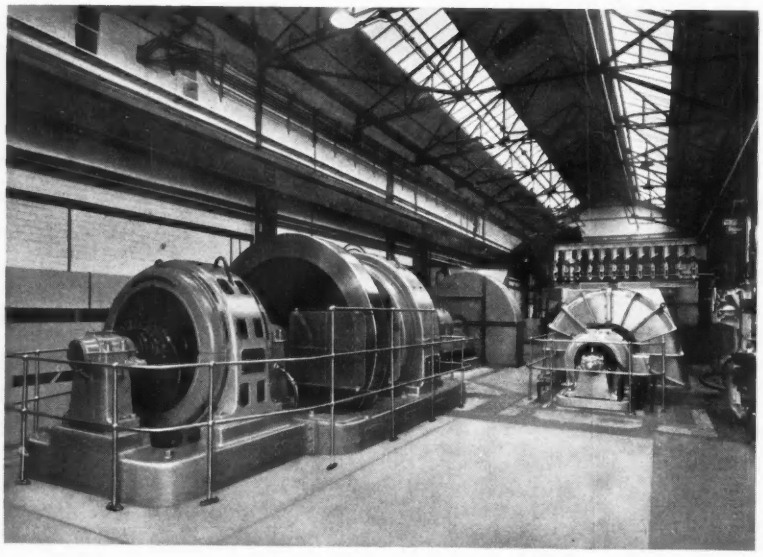

Fig. 38.—Separate exciter driven by a 1,500 h.p. motor and coupled to a 13 ton flywheel. The 750 h.p. motor driving the test alternator is seen on the right.

energy required during this period is supplied by the moving mass of the rotors of the alternator and driving motor. As this mass is very large, the speed of the machine falls very little between the time when the supply is cut off and the actual short circuit applied.

In the first instant of the short circuit, however, the rate of deceleration is comparatively rapid. There is in consequence a heavy torque on the coupling between the driving motor and the main rotor. A Wellman-Bibby coupling is employed in this instance in preference to a solid coupling, and is giving satisfactory results.

In emergency, the driving motor may be used as a brake.

EXCITER.

It should be appreciated that the size of the alternator is not the only determining feature of the testing capacity of the plant. Unless special steps are taken to maintain the flux of the machine during the short circuit period, the high short circuit current reacts quickly on the flux, so that by the time the test switch has opened, the short circuit current has considerably decreased. While the initial peak of the short circuit current determines the mechanical force on the switch, the current at the instant the switch opens is the important factor in determining the rupturing capacity of the switch. It is, therefore, of the utmost importance for a testing set of this type to maintain the flux in the machine as nearly as possible at its original value during the opening of the test switch.

This has been accomplished in the High Power Test Laboratory at Witton by providing an exciter which is the largest in this country employed for such a purpose. The exciter is a machine having a normal output of 1,000 amps at 1,000 volts with a maximum capacity of 4,000 amps at the same voltage. As the alternator is on open circuit before the short circuit is applied, excitation has only to be provided for this particular condition.

A ballast resistance is inserted between the exciter and the alternator rotor which keeps the current and voltage across the rotor within the limits required for open circuit excitation. Just before the test is applied, the ballast resistance is short circuited with the result that the voltage across the rotor is suddenly increased to four or five times the original value. The rush of current thus produced is directed into the rotor of the alternator at the critical moment and is maintained throughout the short circuit period until the test switch opens. Due to the high degree of over excitation which results, not only is the short circuit current of the machine itself maintained near its maximum value, but also, after the switch has opened, the over excitation of the alternator ensures a very quick recovery of the voltage across the switch contacts, thus imitating the effect of a large supply system. Without this provision, the flux of the alternator would have been diminished by the action of the short circuit, and the recovery voltage would be much lower at the moment after the opening of the test switch. The final recovery would also be much slower. This action of the exciter necessarily involves a very large increase in the power it requires during the short circuit, and to avoid this increase being demanded from the driving motor, and therefore from the power supply, a flywheel, weighing 13 tons, is coupled to the motor, the kinetic energy of the flywheel providing the necessary power during the short circuit period. The motor driving the exciter set is switched out of circuit before the ballast resistance is short circuited and the whole of the excitation energy during the short circuit period is supplied by the flywheel.

An interesting consequence of this particular feature is that the exciter set is larger in overall dimensions than the main alternator.

LUBRICATION.

The main bearings of the alternator, exciter and driving motors are lubricated by oil at a pressure of

12 lbs. per sq. in. which is fed by gravity from a 960 gallon reservoir situated on the roof of the machine room. After flowing through the bearings the oil runs into a sump from which it is returned, through a water cooler, to the reservoir by a pump which delivers slightly more oil than the bearings pass, the excess oil returning to the sump through an overflow pipe. Should the auxiliary supply fail, the 960 gallons of oil in the reservoir are sufficient to lubricate the machines while they are being brought to rest. In the event of the return pump failing, the oil level in the reservoir would fall, automatically stopping the driving motors and lighting a warning lamp in the control room.

In order to provide an oil film in the bearings of the 22-ton alternator rotor and the 13-ton flywheel, oil at 1,000 lbs. per sq. in. pressure is injected by two motor driven pressure pumps just before the alternator and exciter are started. These pumps are shut down when the rotor and flywheel have made a few revolutions.

AIR COOLING SYSTEM.

A separate motor driven fan (seen on the left of fig. 21), delivering 50,000 cu. ft. of air per min., provides the necessary cooling air for the alternator and its driving motor. The air is drawn from outside the building and is passed through an inlet chamber fitted with an oil filter having an area of 136 sq. ft. Thence the air is conducted to the fan which delivers it into five separate ventilating chambers in the alternator and driving motor. Two of these are arranged one at each end of the alternator and one in the centre, while the remaining two are arranged one at each end of the driving motor.

The air leaves both machines at the top of the shell and finally escapes through louvres mounted in the centre of the roof. Should the air supply fail, a light signal is shown in the control room.

In the event of a fire starting in the windings of the alternator or driving motor, the air circulating system is immediately and automatically stopped by the closing of shutters at the inlet and outlet sides, and the whole system is flooded with carbon dioxide. Eight 50 lb. cylinders of this gas are provided for this purpose and are sufficient to fill the air chambers of the machine in 30 seconds.

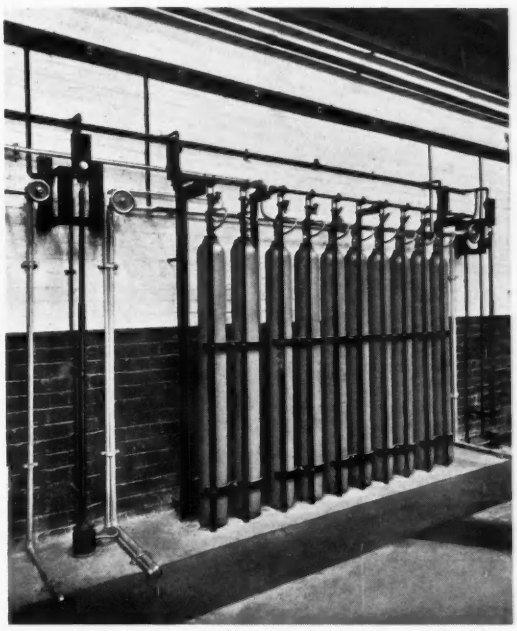

Fig. 39.—Bank of 50 lb. carbon dioxide cylinders and control gear in the generating station.

TEMPERATURE RECORDING DEVICES.

A large number of thermo-couples are inserted in the windings of the alternator and at various other points, which give an indication in the control room of the temperature rise of the vital parts of the machine.

Thermostats are also inserted in the bearings and are employed to shut down the whole equipment should the temperature of any bearing exceed a predetermined value. An audible warning of this event is given in the control room.

[*To be continued*].

A New Lead Extruding Machine.

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Lead — one of the earliest known metals, extracted from its ores and used by the ancient Assyrians, Egyptians and, later, the Romans—was the first metal to be extruded. In the accompanying article the author briefly outlines the history of the metal with particular reference to its extrusion.

He subsequently describes a new machine, developed at the Pirelli-General Cable Works Ltd. which overcomes the serious disadvantages of all machines hitherto used for covering electric cables with extruded lead.

THE high density and softness of lead and the ease with which it is extracted from its native ores, led to its application in very early days to the uses of mankind. Lead water piping, for example, has frequently been dug up by workmen excavating in Rome, Pompeii and other ancient cities and found to be in a perfect state of preservation after having been buried for over 2,000 years.

In this country very interesting specimens of lead piping laid down by the Romans about A.D. 76 in the time of Vespasian have been dug up in Bath, and metallographic examination has shown that the piping was made of cast sheet lead. The sheet lead was cast in a shallow mould approximately 6 ft. long by 1 ft. 3 ins. wide and ½ in. deep, and then bent into a triangular shaped pipe joined by pouring molten metal along the apex (see fig. 1).

Reproduced from "Lead the Precious Metal" by Harn.

Fig. 1.—Portion of lead pipe dug up after having lain in Roman soil for 1,800 years.

Later, lead piping was made by an extrusion process; in fact, lead was the first metal to be extruded on account of its softness. The first recorded patents for such a process were taken out in England in 1797. The early extrusion machines consisted of a cylinder fitted at one end with a piston in the form of a screw so that when the cylinder was filled with lead and heated, the piston could be screwed up to squirt the lead in the form of a rod out of an opening in the bottom of the cylinder. Tubes were extruded by fixing a rod extension to the centre of the piston passing through the opening of the cylinder so that when the piston was screwed up, the metal was forced out in the form of a tube through the annular space between the rod and the hole.

Instead of operating the piston by hand, power was next applied and the machine was used for the manufacture of lead piping. Lead sheet was also manufactured by the extrusion process, a very large diameter pipe first being made and then split longitudinally and flattened out.

In 1869, A. H. Hammon patented the hydraulic press in France. Hammon used his press for manufacturing tin-lined lead pipe, and the design of his press is very similar to that of the normal type of extrusion machines employed at the present time.

In the normal vertical lead press as used for cable sheathing, fig. 2, the cable is passed through a die box G, which is kept at a predetermined temperature immediately under the container I, whilst D is a cylinder to which water under pressure is admitted. The water, acting on the ram E, raises the container I and the ram J, which is stationary, forces the lead around the nipple A, fig. 3. The lead is then forced around the core die B through which the cable is passing and is extruded through the ring die C. The thickness

of lead is determined by the difference between the outside diameter of the core die and the inside diameter of the ring die, and the even thickness of lead is controlled by the adjustment of the ring die C, by means of the bolts D.

The behaviour of lead pipes in service has been found to be extremely variable. Some have stood the test of centuries of service while others employed under similar conditions have deteriorated very rapidly. Such wide divergence in the properties of apparently similar piping have naturally lead to many investigations into the causes responsible, and the work carried out by the Non-Ferrous Metals Research Association since 1925, at the request of electrical cable manufacturers, is of particular interest in this respect. It was found that the failure of lead piping was, in certain cases, due to the inability of the lead to stand up to alternating stresses caused by vibrations in the locality in which the pipes were laid, such as railway lines and highways along which heavy traffic passed. A remedy for this type of failure was found in the adoption of certain alloys more resistant to this type of fatigue. In many other cases, however, the cause of the failure could not be attributed to special local working conditions and it was suspected that the condition predisposing to failure lay with the walls of the pipe itself. The science of metallography was applied to the problem and brought to light the fact that the majority of pipe failures was due to the inclusion of oxide films in the lead walls of the pipes.

The inclusion of oxide films is due to an inherent defect possessed by all intermittently operating lead presses.

When the container of a normal type press is filled with molten lead, the surface being in contact with air, oxidizes rapidly. On recharging the container, the fresh molten lead is poured on top of the oxidized surface of the old lead, and since the fresh charge of lead does not completely melt all the residue of the old charge in the container, all the oxide does not come to the surface of the fresh charge. When the press is again put into operation a certain amount of lead oxide is extruded along with the lead. It has been the custom to skim the surface of the molten metal in order to eliminate the oxide as far as possible, and also to cut off a few feet of the lead extruded immediately after charging. Such precautions, however, although beneficial to some extent, have proved quite inadequate.

It is instructive to consider how the oxide films

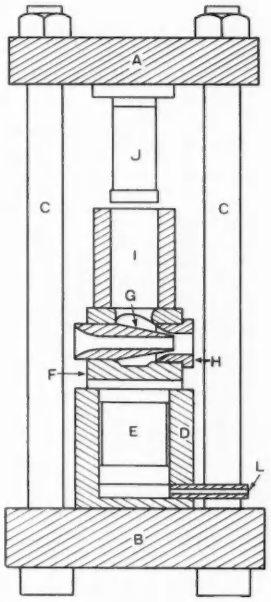


Fig. 2.—Diagrammatic view of vertical type lead press.

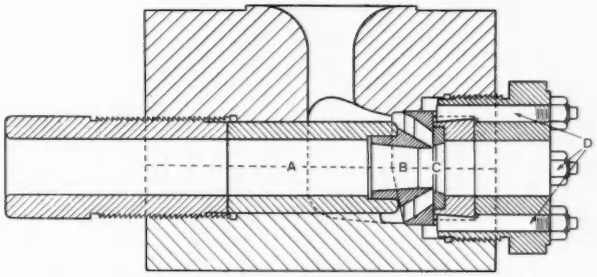


Fig. 3.—Detailed section through lead press die box.

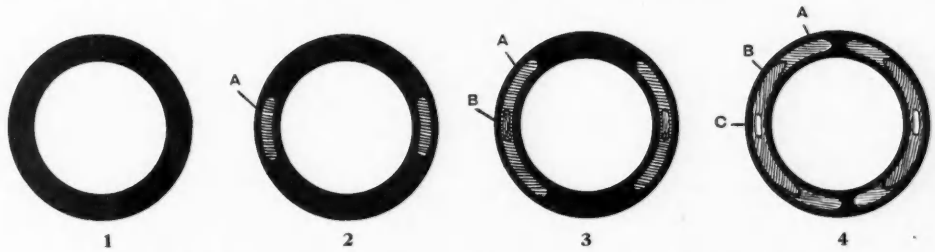


Fig. 4.—Diagrammatic view of tongues of lead representing different charges of lead in the container.

are distributed. Referring to fig. 3, it will be seen that it is necessary to divide the plastic lead stream in order to extrude it in tubular form around the cable so that the two streams of lead have to amalgamate to form the piping.

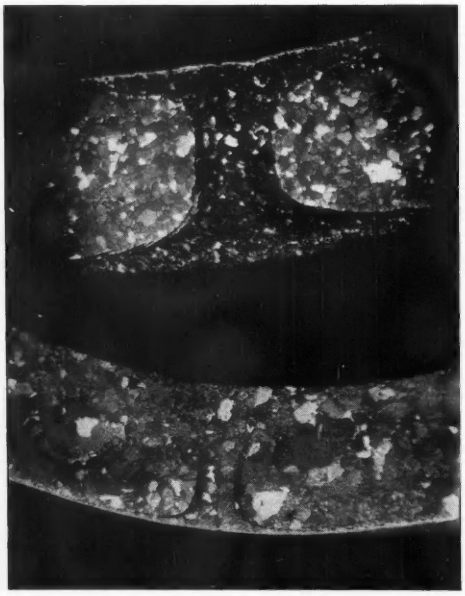


Fig. 5.—A lead pipe showing stages corresponding to diagrams 3 and 4 in fig. 4.

In the internal passages leading to the dies the lead moves forward in the manner of a viscous fluid, motion being rapid in the centre of the channels and very slow at the confining walls. It follows, therefore, that lead from the new charge A in the container will make its appearance in the cable sheath long before all the lead from the previous charge has been swept out from the feeding channels, and a thin film of oxide will separate the portions of lead representing the old and new charges, as may be seen in the second illustration of fig. 4, which shows this diagrammatically.

As extrusion proceeds, an increasing proportion of the circumference of the sheath consists mainly of the new charge A lead (diagram 3) and eventually the tongues of this new lead meet at the top and bottom points (diagram 4). Actual photographs of the lead, fig. 5, show stages corresponding to diagrams 3 and 4 of fig. 4.

By this time the container has had to be charged again, and lead from this latter charge B may have reached the top of the circumference, and as before, will also flow round to the bottom point, eventually overtaking the last pair of tongues of lead which have now merged into a single seam at the lowest point.

It is at this point, where the successive tongues of new lead converge, that the common defect known as split lead originates. The weakness is due to the accumulation of numerous thin layers of metallic lead separated by oxide films, fig. 6, each layer corresponding to a single charge of lead poured into the press container.

It will thus be seen that a longitudinal seam or weld extends through the length of a cable sheath and that films of oxide are deposited along a considerable portion of the weld.

To overcome the weakness due to defective welds, various ideas have been suggested from time to time. The lowering of gas jets into the lead container in order to melt the residue of the previous

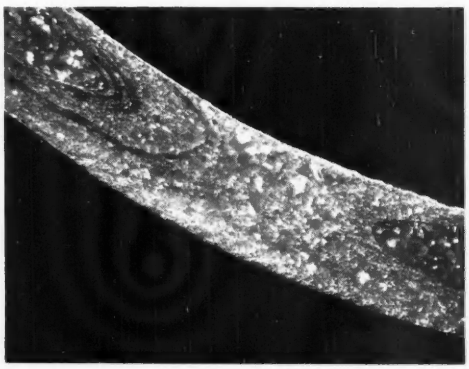


Fig. 6.—Photomicrograph showing layers of metallic lead separated by oxide films.

charge before pouring in the fresh charge has been suggested—the designing of special die chambers, so that the weld instead of being in the form of a butt joint as shown diagrammatically in fig. 7, is changed to a long scarf joint. It is obvious, however, that these methods do not obviate the weakness due to the oxide films which collect at the weld. That this weakness in lead sheathing is due to oxide and not necessarily to the presence of welds themselves, is substantiated by many investigators. King and Gray, for example, have stated[1] that they carried out experiments using oxide free lead with a bridge

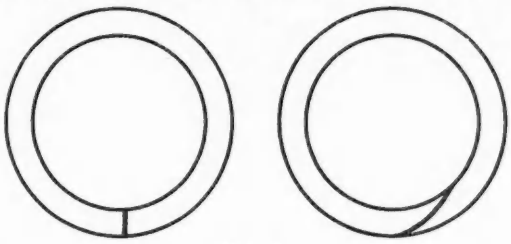


Fig. 7.

Butt weld in sheath produced in normal type press.

Scarf joint in sheath produced on press with modified die chamber.

die and no weakness could be detected in the weld, and they assert that of all causes of failure of lead sheathing, oxide inclusions take priority.

1—J.I.E.E. Transactions, Vol. 45, Part 3.

No modification to existing intermittent presses can be entirely successful because they do not prevent the inclusion of lead oxide and in this connection it is interesting to note that the straight through press, although affording some advantages in the provision of an annular scarf weld joining the lead between charges, does not eliminate lead oxide as can be seen from fig. 8, which is a photomicrograph of parts of a lead pipe section taken at a weld.

The new lead extruding machine, which has been developed at the Pirelli-General Cable Works, represents a radical departure from accepted practice. It is continuous in operation and produces sheathing entirely free from lead oxide.

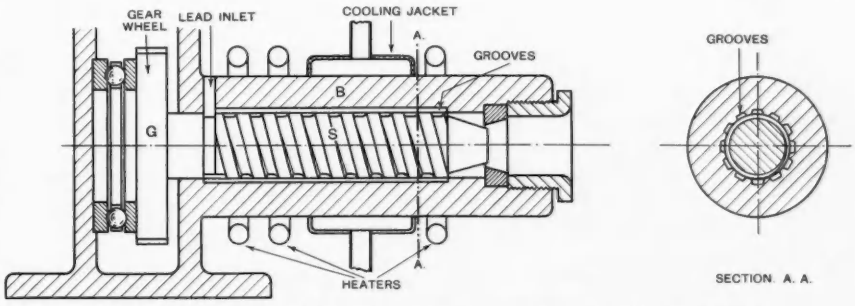


Fig. 9.—Diagrammatic arrangement of new lead extruding machine.

The principle upon which the machine functions will be readily understood from an examination of the elementary diagram shown in fig. 9. Referring to this diagram, S is a steel screw driven by a gear wheel G, revolving in the cylindrical barrel B. The bore of the barrel is provided with a number of channels or grooves. Molten lead enters at the lead

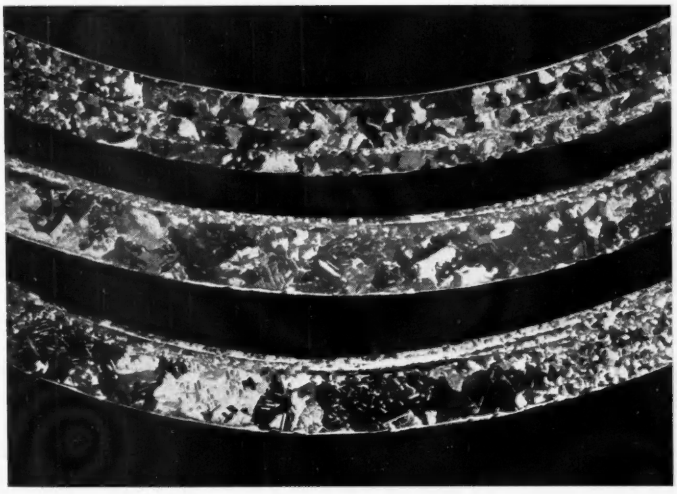


Fig. 8.—Photomicrographs of lead pipe sections taken at a weld.

entry, this part of the machine being maintained at a suitable temperature by means of heaters. The lead fills the longitudinal grooves and the threads of the screw. Owing to the presence of the cooling jacket, the metal in the grooves becomes solid. As the screw rotates it tries to carry the lead lying in its threads around with it, but owing to the friction between the lead in the threads and the solid lead in the keys, considerable resistance to rotation is set up. As the co-efficient of friction between lead and steel is less than between lead and lead, the lead spiral lying in the threads of the steel screw is forced forward through the machine into the die chamber very much in the same way as the tool carrier of a lathe is forced forward by the rotation of the leading screw. The plastic lead is compressed to a homogeneous mass in the die chamber and forced through the dies and out of the machine in the form of a pipe.

It will be realised that in the primative form of machine under description the cone die is carried by the revolving screw and must also revolve, whilst the ring die is stationary. The resulting pipe is extruded with a considerable twist which is not desirable especially when the machine is used for covering cable. Considerable development was therefore necessary to produce a machine in which the dies were both stationary.

Fig. 10 shows a sectional view of the machine in its present form. The machine is driven by an electric motor, and consists essentially of a stationary tube through which the cable travels, carrying a core die at one end and surrounded by a revolving hollow steel cylinder. This steel cylinder has screw threads on its inner and outer surfaces which co-operate in a manner already described with the longitudinal grooves forming keys in the bore of the barrel and the outer surface of the stationary tube. Lead is admitted to the barrel and passes through ports in the revolving cylinder to the underside of the tubular screw as well as the outer side, thus giving a double extrusion effect. The tubular screw is driven through a gear unit comprised of three pairs of gears (1), (2) and (3), made of hardened steel, the first reduction being profile ground to ensure silent running.

To facilitate construction and assembly the reductions (2) and (3) are mounted in cast iron, subsidiary casings (4) and (5). The final gear (1) which is mounted on the main extrusion screw (6), is housed in a steel casing (7) designed to withstand a thrust of 600 tons.

The extrusion screw (6) is provided with a shoulder

which forms a base for the gear (1) which in turn forms a supporting face for the large thrust race (9), which takes the reaction of the screw when extruding. The back end of the thrust race is mounted in a steel flange piece (10) fastened to the steel casing (7), thus giving ample rigidity when the load is applied.

When the load is released, springs (12) force the thrust race (11) forward on to the shouldered portion of the casing so that there is no danger of the balls dropping out of their tracks.

Attached to the steel flange (10), which also carries one of the main roller bearings (14), is a spigotted steel flange (8) to which is fastened a stationary tube (15) and located by means of keys (16), thereby preventing any rotation. The roller bearing (17) is mounted in the front end of the steel casing (7), thus giving a long bearing span and ensuring ample support of the screw (6). An oil retainer (18) is provided in front of the roller bearing (17) to prevent any leakage of oil into the extrusion portion of the machine. The screw (6) which protrudes into the extrusion chamber (19) is made of high tensile heat-treated steel and has machined annular grooves (20) which form a lead retainer preventing any lead running back into the gear unit. The screw is also provided internally and externally with a thread (21) designed for the production required. In the case of the outer and inner extrusions the lead in the threads is forced forward by means of the outer and inner screw respectively, keys (22) and (23) being provided to prevent rotation of the lead about the axis of the machine and to allow horizontal movement only to take place.

The lead entry (24) for the outer extrusion is provided on the top of the barrel, while lead for the inner extrusion is admitted through portholes (25). Annular grooves (27) provided on the stationary tube act as a retainer preventing the passage of lead to the back portion of the machine. The extrusion chamber (19) is fastened by means of bolts to the steel casing (7). Inserted in the extrusion chamber (19) is a detachable sleeve (29) held in position by a retaining nut (30). The sleeve, in addition to having keys cut on the inner surface, is provided with cooling channels (31) for the purpose of cooling the lead to the temperature necessary for extrusion.

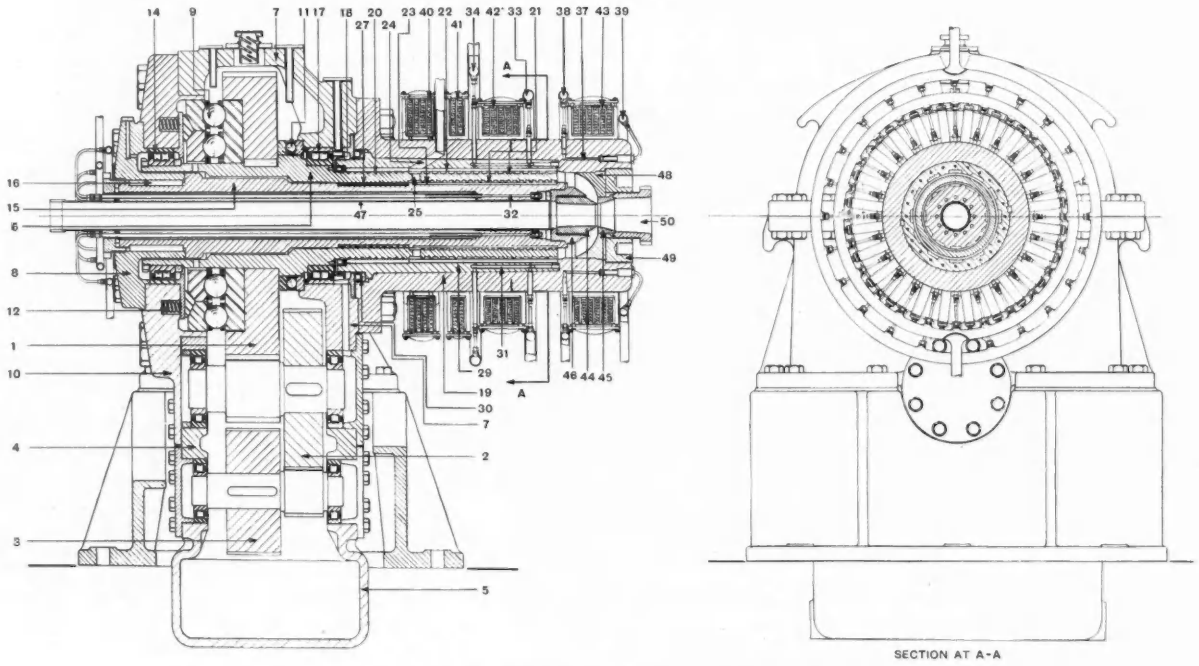


Fig. 10.—Sectional view of the new lead extruding machine.

For the inner extrusion, cooling (32) is also necessary and this is provided for in the stationary tube (15). A circular manifold (33) forms the outlet. The inner cooling for use with the inside extrusion is also supplied with two circular manifolds on the back end of the machine. On the front part of the extrusion chamber (19) further cooling has been arranged to control the temperature of the lead in the compression chamber. This again is in the form of longitudinal channels (37) the inlet of the cooling being at (38) and the outlet at (39).

The water used for cooling purposes is distilled or softened and flows in a closed circuit formed by radiators (not shown on the drawing) and suitable tanks. By this means, formation of scale in the channels is entirely avoided.

The initial heating of the machine is effected by means of three induction coils (40) and (41) back

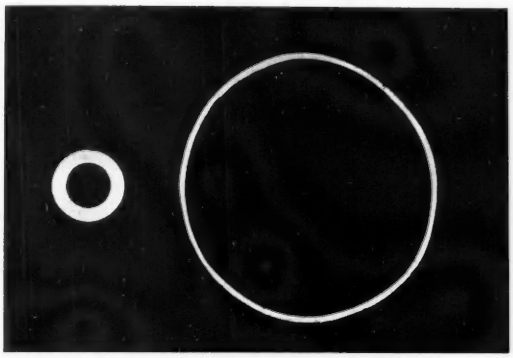


Fig. 11.—The relative size of pipe before and after stretching.

coils, (42) middle coil and (43) front coil. During the normal functioning of the machine the lead in the back portion of the extrusion chamber must be maintained in the molten state and the back coils (40) and (41) are used for this purpose.

The core die (44) is supported by a holder (46), securely fastened to the stationary tube (15). The ring die (45) is centralized by a shaped ring (48) which is held by a front screw (49). An adjusting screw (50) provides the necessary adjustment of the ring die for variation of thickness in the lead. A tube (47) insulated from the machine by an air gap, protects the cable core while passing through the hot portions of the machine.

The machine is made in three sizes—the large size is capable of sheathing cables up to 5 ins. diameter under the lead; the medium up to 3 ins., and the small up to $1\frac{1}{2}$ ins.

The minimum diameter of cable which can be sheathed on each size depends on the maximum linear speed of the sheathed cable with which the operators can cope.

The large size machine will extrude up to 4 tons of metal per hour, the medium size up to $2\frac{1}{2}$ tons and the small size up to 0.8 tons. Fig. 12 shows an early form of the extruding machine, and fig. 13 one of the medium size machines in operation at the Pirelli-General Cable Works.

OPERATION.

The machine is very easy to operate. The heating coils are energized to heat the barrel to about 300°C at which point the driving motor can be started up to turn the machine over. If a lead supply valve is used it is now opened to admit lead to the machine, or if no valve is used, the supply is controlled by melting or solidifying the lead in the connecting pipe between the lead pot and machine.

As soon as molten lead has access to the machine, water is circulated through the cooling channels around the barrel in order to create the plastic condition in the lead necessary to cause the reaction between the lead in the screw threads and that in the channels.

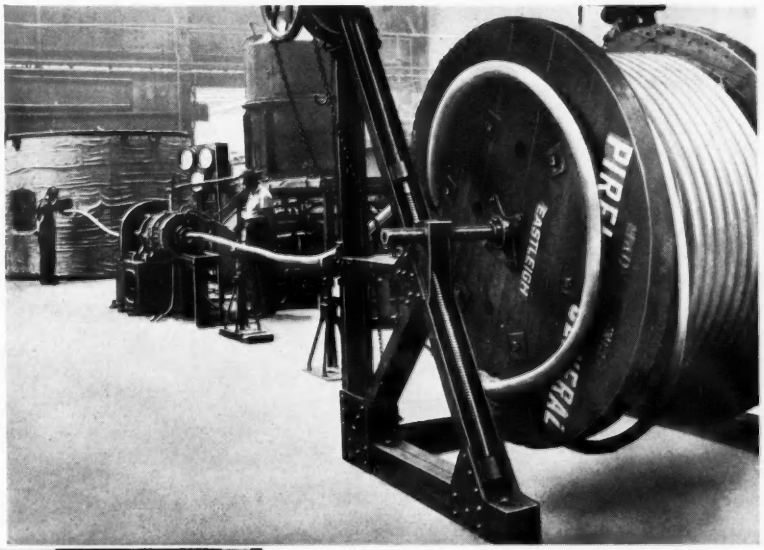


Fig. 12.—An early form of the new lead extruding machine.

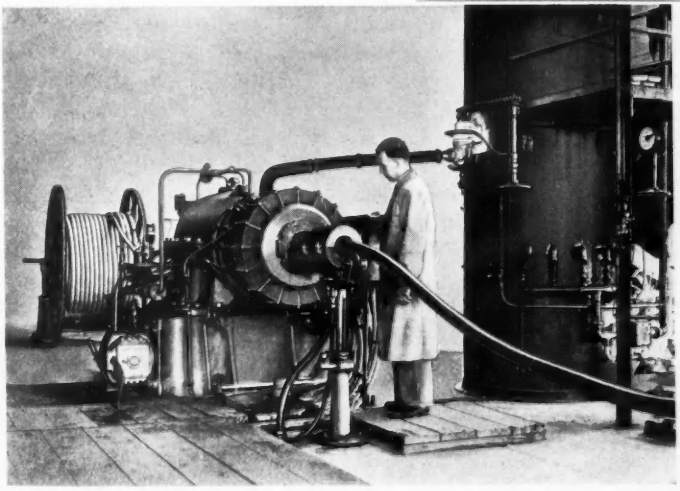
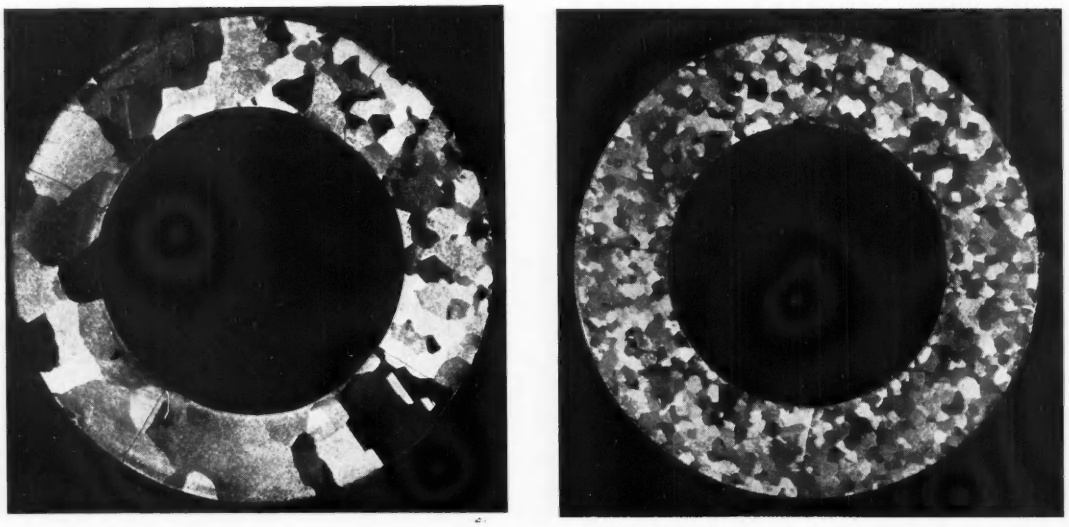


Fig. 13.—New lead extruding machine at Pirelli-General Cable Works.

The speed of the lead pipe or cable sheath can be controlled by changing the degree of cooling, and once this has been set to a suitable value the machine will continue to extrude as long as molten metal is fed into it. The weight of metal extruded is constant throughout the range of a particular size of machine and does not vary with the size of pipe extruded. The output in tons per hour is higher than that obtained from corresponding hydraulic presses because, although the actual speed of the extrusion may be lower, it is continuous, whilst the hydraulic press must stop frequently for the refilling of the container and the setting of the metal.



(a) (b)

Fig. 14.—Section of a water pipe made with a four arm spider die support in the extruding machine.

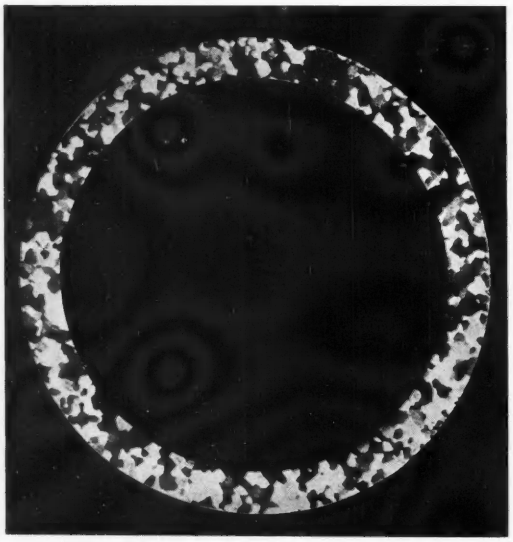


Fig. 15.—Section of a pipe made without a die spider.

It has been shown that the crystalline structure of the pipe made on the extrusion machine is free from lead oxide, and this freedom is not affected by the use of spiders or die supports if it should be found necessary to use these aids to extreme accuracy in the dimensions and concentricity of the pipe.

Fig. 14 illustrates a section of a water pipe made with a four arm spider die support in the extrusion machine, showing the flow lines: (a) shows crystal formation in a pipe allowed to cool slowly in air while (b) shows the crystal formation in a pipe cooled quickly with water.

Samples of water pipe made in this machine, using a four arm spider support to the core die, have been tested by stretching them to four times their mean diameter as shown in fig. 11, without any weakness developing in the wall. A section of a pipe made without a die spider is illustrated in fig. 15.

Experience with a machine of this type has proved that, because no air enters with the lead, there is an entire absence of lead press defects such as pin holes or air blisters, red lead, and weak seams, so that in the case of power and telephone cables a valuable saving in stripping defective lead sheaths is obtained. The cost of the machine is thus recovered in a comparatively short time.

The early form of extruding machine shown in fig. 12 has been in operation for two years, sheathing cables for the most important contracts for super-tension working with very satisfactory results.

Turbo-Blowers and Turbo-Compressors.

PART III.

By B. POCHOBRADSKY, M.I.Mech.E.

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GOVERNING.

THE object of governing is to meet the changing requirements of the plant served by the turbo-blowers and compressors. In addition, it is necessary to prevent the so-called "pumping" or "surging" which occurs, unless means are introduced to prevent it, when the gas flow is reduced to the point at which the delivery pressure at a given speed reaches its maximum.

In general, the output should be adjustable: either the gas quantity or the delivery pressure (in case of exhausters suction vacuum), or both, should be capable of being set at will within the limits for which the machine was designed.

In the particular case of turbo-blowers serving smelting furnaces, the air quantity flowing through a charge should remain constant, although the resistance to the air flow changes on account of alteration of the area of openings in the charge as a result of the smelting process. These turbo-blowers are provided with "constant volume" governing, that is to say, the air quantity is maintained constant within small limits, while the delivery pressure is determined by the momentary resistance in the furnaces. Where air is required for power purposes, drills, hammers, haulages, riveters and the like, the pressure of the compressed air should be maintained constant while the air quantity demand varies. For such cases, turbo-compressors are provided with "constant pressure" governing.

If the pressure-volume diagrams, figs. 12 and 13[1] are examined, it is seen that any given output within the working range can be obtained by operating the machine at a certain speed. By suitably varying the speed, either a constant pressure for varying volume or a constant volume for varying pressure can be secured. This speed variation is notably easy to achieve when the driving machine is a steam turbine, gas, or oil engine, or certain types of electric motors. There are, however, instances where the driving motor has practically a constant speed and the method of varying the speed to obtain either constant pressure or constant volume governing is not applicable. In such cases the machine must be designed to give the maximum specified duty at the

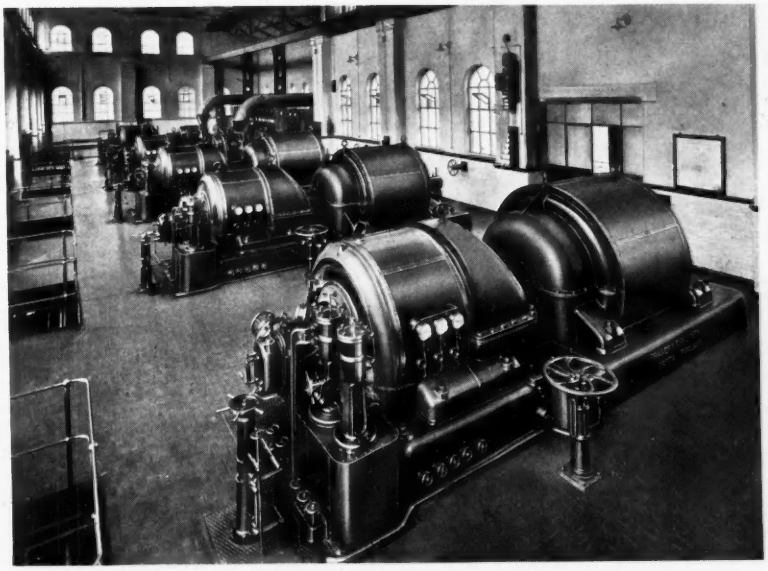


Fig. 21.—Three Fraser & Chalmers turbo-blowers, each delivering 25,000 cu. ft. of free air per minute against a pressure of 12 lbs. per sq. inch (blast furnace service).

1.—G.E.C. Journal, Vol. VI., No. 4, p.p. 214 and 215.

available speed, and any smaller duty either in volume or pressure, or both, is obtained by throttling at the inlet or the delivery.

It is of interest to consider a turbo-blower driven by a constant speed motor and delivering a constant air quantity by means of throttling the delivery pressure. Obviously, the motor output remains constant and equal to that for the maximum duty of the turbo-blower, although the duty actually required may be substantially smaller on account of a lower resistance in the furnace served by the turbo-blower. From this and similar examples it is clear that governing, by means of throttling, is generally less economical than governing by means of speed variation.

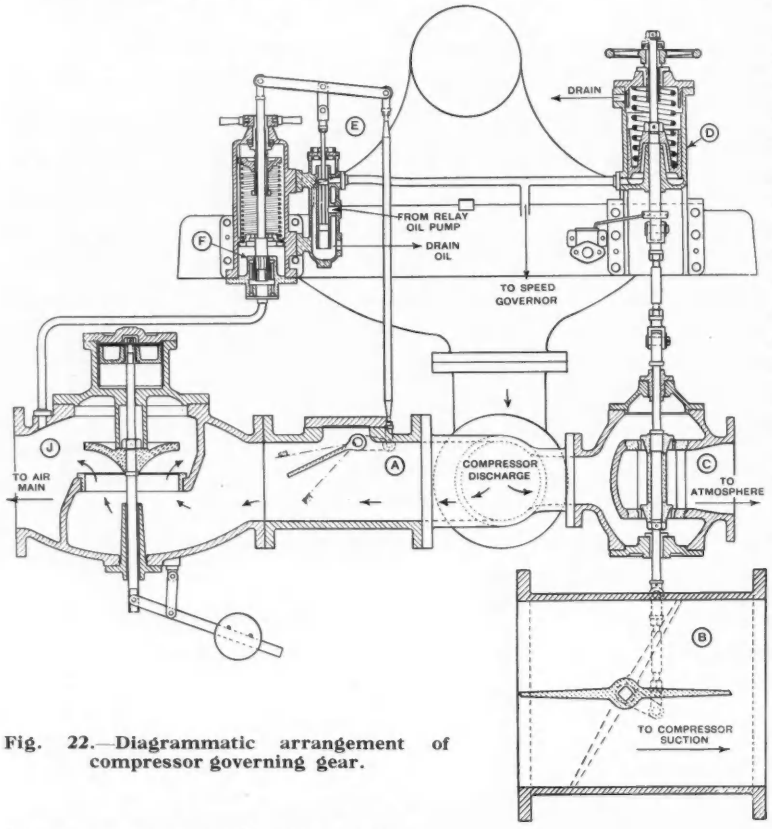


Fig. 22.—Diagrammatic arrangement of compressor governing gear.

Following on these general remarks it is proposed to describe in more detail typical constant pressure, constant volume governors and anti-pumping devices.

ANTI-PUMPING DEVICE AND CONSTANT PRESSURE GOVERNOR.

(*a*) *Variable Speed Motor.*

The Fraser & Chalmers anti-pumping device fitted to a turbo-compressor makes it possible for the compressor to deliver any quantity of air down to zero without pumping. In the event of the demand of air being below the natural pumping limit of the compressor the delivery of air into the air mains takes place intermittently. The compressor will then deliver air for a limited time into the air mains at a rate exceeding its natural pumping limit, and afterwards will cut off the air delivery until the pressure in the air mains has fallen to a set limit, when the charging up of the air mains again starts automatically. This process repeats itself so long as the demand of air remains below the pumping limit. During the period of non-delivery, the suction pipe is practically closed by means of a butterfly valve and the delivery pipe opened to atmosphere through the relief valve. A very small volume of air only is allowed to pass through the compressor and a vacuum is thereby created in the machine so that the power necessary to drive the compressor is only a small percentage of the full load duty.

The governing gear is shown in fig. 22 in the position when the compressor is delivering into the air mains, namely the butterfly valve B is open, the relief valve C

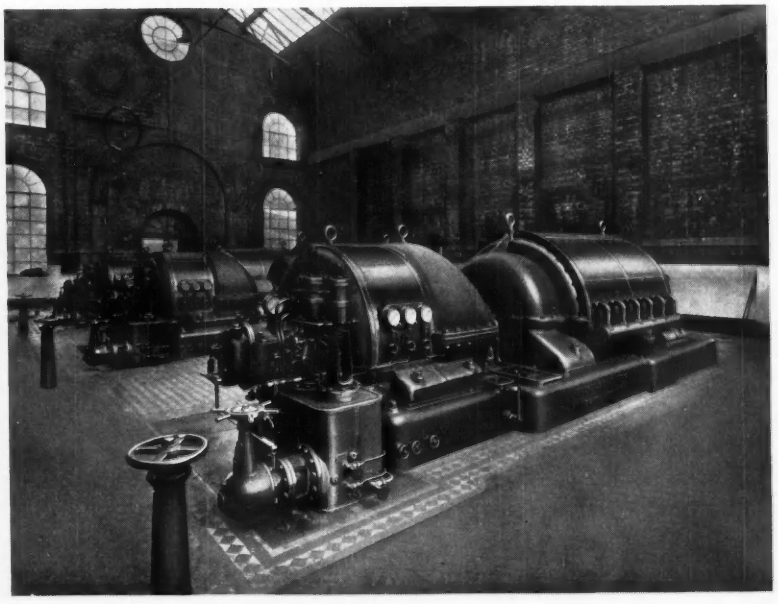


Fig. 23.—Three turbo-blowers each delivering 36,000 cu. ft. of free air per min. against a pressure of 16 lbs. per sq. inch (blast furnace service).

closed, the non-return valve J open, and the air piston F in its extreme top position. If the demand for air diminishes and approaches the pumping limit the control valve A closes and moves oil pilot valve E into such a position that pressure oil is admitted underneath power piston D, thereby closing the butterfly valve B and opening relief valve C. As soon as the air escapes through the relief valve C, the non-return valve J automatically closes the compressor delivery against the air mains. As the demand of compressed air still continues the pressure in the air mains falls and causes the air piston F to move into its lowest position by means of the spring on the top side of the piston. This movement brings oil pilot valve E below its neutral position and the oil drains again out of the power cylinder E, closing the relief valve C and opening simultaneously the butterfly valve B. The compressor will now deliver into the air mains again and as the pressure in them rises to its normal value the air piston F is lifted into its top position. The air passing from the compressor into the air mains automatically opens the non-return valve J and forces the control valve A into a higher position. The gear has now returned to its original setting ready for the above described cycle to be repeated.

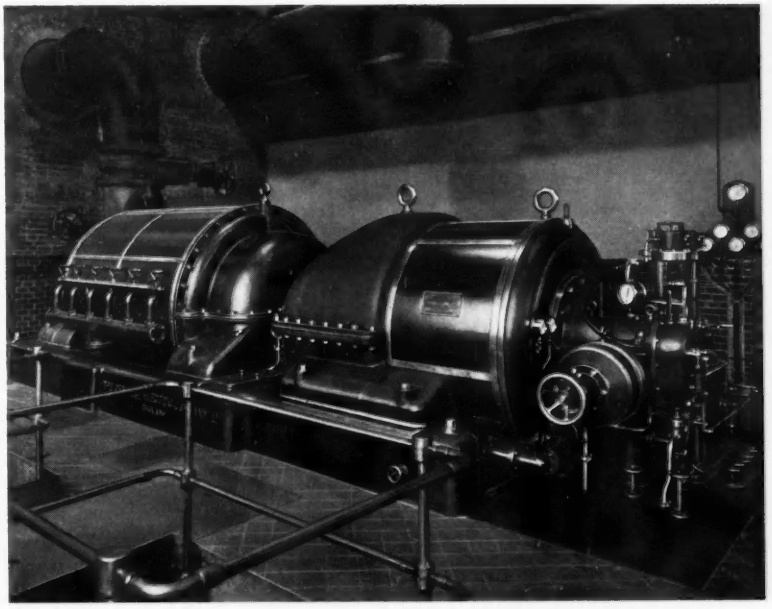


Fig. 25.—Fraser & Chalmers turbo-blower, delivering 30,000 cu. ft. of free air per minute against a pressure of 25 lbs. per sq. inch (Bessemer service).

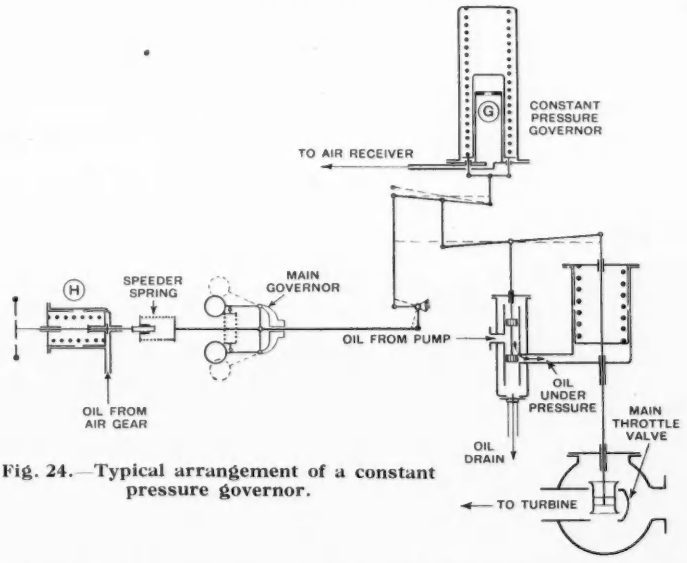


Fig. 24.—Typical arrangement of a constant pressure governor.

A typical arrangement of a constant pressure governor is shown diagrammatically in fig. 24. It consists of an air cylinder G connected with the delivery air main. An increase in air pressure will lift the air cylinder and move the oil pilot valve so that the steam throttle valve or valves close and cause the turbo-compressor to reduce the speed. *Vice versa*, a drop in air pressure will move the air cylinder downwards and the oil pilot valve will admit pressure oil underneath the power pistons of the steam throttle valves of the turbine. The speed will now increase and, in consequence, a larger volume of air will be delivered by the compressor. When the air governing gear opens the relief valve and destroys the pressure on the delivery side of the compressor, the constant pressure governor will tend to overspeed the turbine. In order to prevent this, a small oil operated power piston H is arranged in the speeder gear of the turbine governor. The oil supply is controlled by pilot valve E (fig. 22). Simultaneously with the relief valve C opening, the power piston H moves under oil pressure so as to place the speeder spring under tension, thereby reducing the turbine speed. As soon as the relief valve C closes again, the oil is simultaneously released from the power piston H and the speeder spring placed under compression. The speed rises until the constant pressure governor G takes control of it.

(*b*) *Constant Speed Motor.*

Fig. 26 shows a typical anti-pumping device and constant pressure governor for constant speed drive.

The delivery main from the compressor is connected with the bellows piece, or diaphragm, in the regulator G, which is of the Arca type. An increase in the air pressure causes the impact plate

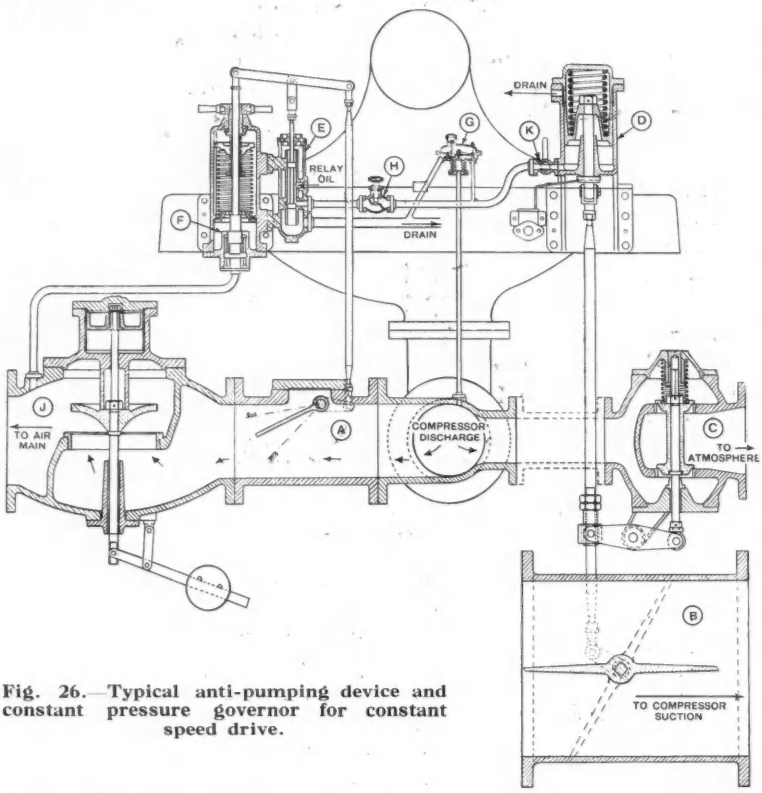


Fig. 26.—Typical anti-pumping device and constant pressure governor for constant speed drive.

of the Arca regulator to move away from the oil discharge orifice with the result that the oil pressure under the power piston D diminishes. The power piston D will therefore fall under the force of the spring and gradually close the butterfly valve B until the desired air pressure in the delivery main is re-established. The smaller the volume of air passing through the compressor, the nearer the butterfly valve is to its closed position and *vice versa*. If now the demand for air approaches the pumping limit, the control valve A closes and moves the oil pilot valve E into such a position that the pressure oil is drained from underneath the power piston D, thereby closing the butterfly valve B and opening relief valve C. As soon as the air escapes through the relief valve C the non-return valve J automatically closes the compressor delivery against the air mains. As the demand for compressed air still continues, the pressure in the air mains falls and causes the air piston F to move into its lowest position by means of the spring on the top side of the piston. This movement brings oil pilot valve E below its neutral position and pressure oil is again admitted to the power cylinder D, closing the relief valve C and opening simultaneously the butterfly valve B. The compressor will now deliver into the air mains again and as the pressure in them rises to its normal value the air piston F is lifted into its top position. The air passing from the compressor into the air mains automatically opens the non-return valve J and forces the control valve A into a higher position. The gear has now returned to its original setting ready for a similar cycle to be repeated.

For the purpose of starting, the valve K is shut. The butterfly valve B will then be closed and the relief valve C opened. With this setting, the compressor in running up to speed, will require a minimum of starting torque. Opening the starting valve K admits pressure oil underneath the power piston D. The butterfly valve will then open, the relief valve close, and the compressor will deliver into the air mains.

CONSTANT VOLUME GOVERNOR.

Constant volume really implies constant weight, but as the specific gravity of gas usually changes very little in course of operation, the expression constant volume has been generally adopted.

If a gas having a velocity V_p and absolute pressure P_1 flows through the throat of an orifice or nozzle where it acquires a velocity V_m and absolute pressure P_2, the following theoretical relation exists:

$$\frac{V_m^2 - V_p^2}{2g} = \int_{P_1}^{P_2} -v\,dP$$

For small pressure differences the specific volume v may be taken as constant, and

$$\frac{V_m^2 - V_p^2}{2g} = v\,(P_1 - P_2)$$

or if W = weight of gas per sec.
F_m = area of nozzle throat.
F_p = area of pipe before nozzle.

then $$\frac{W.^2 v}{2g}\left(\frac{1}{F_m^2} - \frac{1}{F_p^2}\right) = P_1 - P_2$$

In other words, for a given pipe and nozzle, $W.^2 v$ is approximately proportionate to the pressure difference $P_1 - P_2$.

If W changes, it produces a change in $(P_1 - P_2)$ and this pressure change is used to operate through a relay a mechanism which will either alter the speed of the machine or introduce a throttling effect, so as almost to restore the original W; that is W is kept

almost constant. If the specific volume v varies appreciably, a compensating device for that variation can be added.

A Fraser & Chalmers constant volume governor

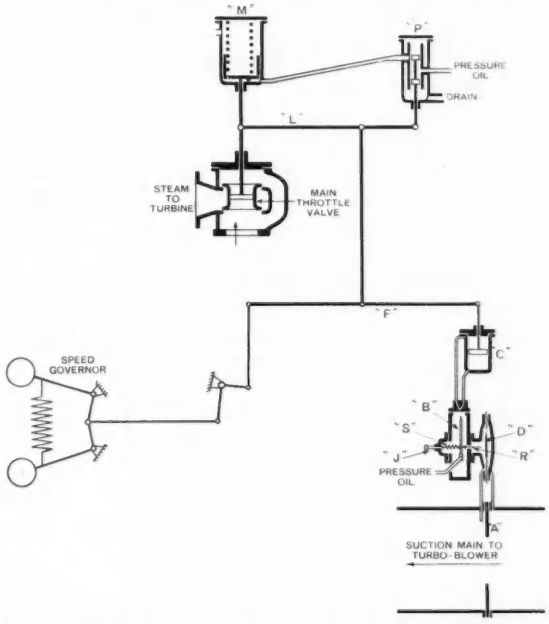


Fig. 27.—Fraser & Chalmers constant volume governor applied to a steam turbine driven turbo-blower.

is shown diagrammatically in fig. 27, as applied when the turbo-blower is driven by a steam turbine. In the suction main is inserted an orifice A. The pressure difference before and at the throat of the orifice acts on the flexible diaphragm D of an Askania regulator. The deflection of the diaphragm is transmitted by a push rod R on to the pivoted jet pipe B, the latter being supplied with pressure oil. The spring S balances elastically the force on the diaphragm D. The compression of this spring is adjustable. Facing the jet pipe outlet are two stationary small orifices adjacent to one another and connected one to the top and one to the bottom of the control cylinder C. The jet pipe B is supplied with oil under pressure and the oil leaving the outlet of the jet pipe with high velocity sets up pressure on the face it strikes. When the jet pipe is in the middle position the pressure set up in the two small orifices will be equal and the piston in the control cylinder C will remain stationary; if the jet pipe moves slightly to the left, as a result of increased volume of gas passing through the orifice A, the pressure will be increased in the top of the cylinder C and reduced in the bottom; hence its piston will move downwards. The lever F connecting this piston and the speed governor (which is set in an inoperative position, acting merely as an emergency device and coming into action only at a slightly higher speed than the maximum speed of the working range of the machine), in conjunction with the lever L, will cause the pilot valve P to move downwards, thus allowing oil from the main power cylinder to escape. The lift of the throttle valve is thereby reduced and the speed of the turbine lowered until practically the original gas volume is restored. Similarly, if for some reason, such as the delivery pressure of the blower being increased, the gas volume tends to fall, the jet pipe moves slightly to the right and the piston in the control cylinder rises, with the final result that the lift of the turbine throttle valve is increased, increasing the speed of the turbine until the original gas volume is restored. By means of the adjustment J the tension of the spring S is varied, which allows the regulator to be set at will for the various pressure differences acting on the diaphragm D, and therefore for various gas volumes passing through the orifice A to the turbo-blower.

It will be understood that, in the case of the constant speed drive, the constant volume governor will operate a throttle valve in the inlet or outlet of the turbo-blower instead of the turbine throttle valve, as just described.

There are, of course, instances where turbo-blowers are controlled primarily by the speed governor of the driving machine, the governor

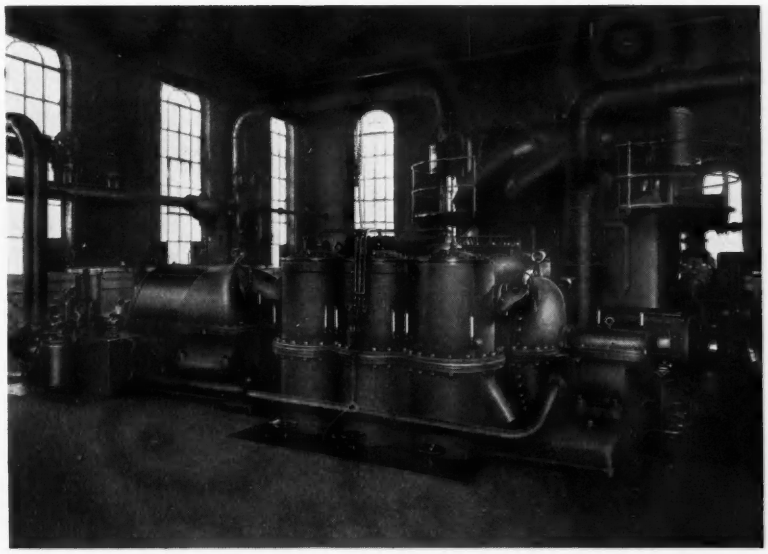


Fig. 28.—Fraser & Chalmers high pressure turbo-compressor, delivering 10,000 cu. ft. of free air per minute against a pressure of 80 lbs. per sq. in.

having a considerable range of speed adjustment.

ANTI-PUMPING DEVICES.

Apart from the anti-pumping devices already described, other devices are available for special cases in which pumping occurs. The simplest is a relief valve inserted in the delivery. When open, this valve relieves air to atmosphere or back into the machine which can then operate just above the pumping limit, delivering partly to the point of use and partly through the relief valve. The relief valve may be operated by hand, by a non-return valve in the delivery, or by the quantity of gas delivered to the point of use.

A turbo-blower or turbo-compressor can run steadily without any surging when delivering no gas but maintaining a delivery pressure somewhat below the maximum, provided there is a slight return flow of gas from the delivery main into the compressor delivery and through the compressor in the direction opposite to the normal one. By the provision of a small connection between the delivery main and the compressor delivery (this connection remaining unaffected by the non-return valve), a return flow will be automatically created immediately the compressor output falls below the pumping limit and so long as the return flow is maintained, the compressor will run without surging. If the pressure in the delivery main gradually falls, the return flow will be gradually reduced until the compressor automatically restarts against the diminished pressure in the delivery main. Should the pressure fall in the delivery main be excessive, the return flow may be stopped by means of a valve which closes when a certain permissible pressure fall has been reached.

APPLICATIONS AND ADVANTAGES.

Turbo-blowers and compressors are used in many industries for the supply of air required for chemical reaction in metallurgical processes or in gassification of coal; for exhausting gas from retorts and coke ovens, and forcing it through pipe lines, or other parts of the plant; for compressing various gases used in sugar factories and in the chemical industry; for the supply of air for sand blasting in foundries, or for creating an air current for the pneumatic conveying of grain, coal, ash, sawdust and other materials; for blowing out the diving tanks of submarines; for the aeration of liquids; for scavenging and supercharging of gas and oil engines; for compressing refrigerants in large refrigerating plants; for compressing air used for power purposes in pneumatic tools and machines. A few of these applications may be described briefly.

The iron and steel industry uses turbo-blowers for blast furnace and Bessemer converter and cupola service. The duty of the blast furnace turbo-blower depends chiefly on the output of the blast furnaces, their height and the quality of charge. For a given charge the air quantity delivered should be constant, though the resistance to the passage of air through the charge varies on account of the varying condition of the charge itself. For this reason turbo-blowers for unit service are equipped with a constant volume governor.

In Bessemer converters the air has to be forced through a depth of molten metal and the turbo-blowers for this work are designed for pressures of 22 to 30 lbs. per sq. in., the large variation of air quantity required during one blowing period being obtained by speed variation.

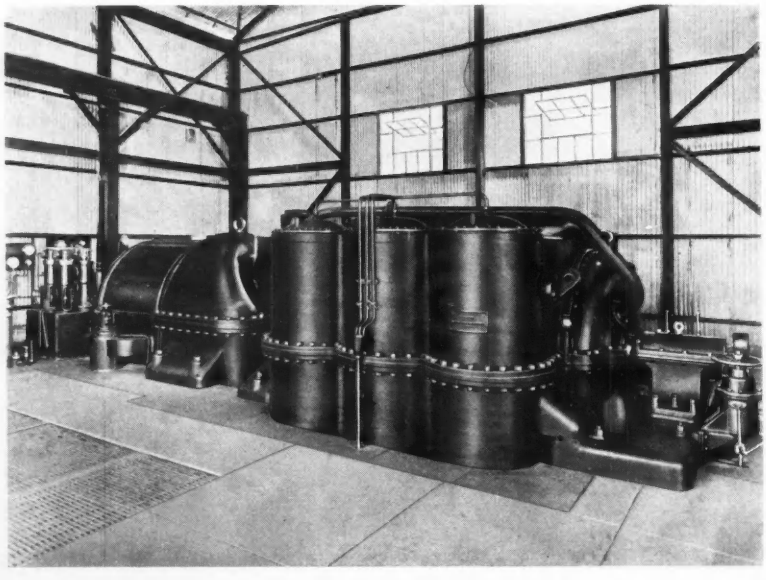


Fig. 29.—Fraser & Chalmers turbo-compressor, delivering 36,000 cu. ft. of free air per minute against a pressure of 100 lbs. per sq. inch.

The cupola used for melting pig iron for the Bessemer converter, open-hearth furnace, or in the foundry, may be served by a turbo-blower delivering at a pressure of 1 to 2 lbs. per sq. in. The copper smelting industry uses turbo-blowers delivering air to copper converters at pressure of about 15 lbs. per sq. n.

In the manufacture of producer gas, a suitable turbo-blower would deliver air at a pressure of about $1\frac{1}{4}$ lbs. per sq. in.; the air is then mixed with steam and preheated before it reaches the producer for gassification of coal.

In gas works, coke oven works

and low temperature carbonization works, turbo-blowers are used as gas exhausters and boosters for exhausting the gas from retorts or coke ovens, and forcing it through pipe lines and through other parts of the plant; they have to maintain a slight vacuum at the inlet and a pressure at the outlet, the whole pressure increase being generally effected in one, two or three stages. These machines are provided with drains for tar and, in order to prevent air leaking in, or gas leaking out, the labyrinth glands are combined with a water seal.

For the pneumatic conveying of solid materials or for the aeration of liquids, turbo-blowers of one to three stages will meet most requirements. Scavenging of two-cycle oil engines of large output is effected by turbo-blowers in preference to built-in reciprocating scavengers on account of the comparatively small space occupied and their smaller weight; these turbo-blowers are usually driven by electric motors, or through gearing by the engine itself, and a single stage blower is frequently quite capable of meeting the service conditions.

It is well known that the output of an internal combustion engine depends on the weight of air charged into the cylinders; engines at high altitudes give less output than they would at sea level; such an engine would give a higher output if supplied with precompressed air than if supplied with atmospheric air. To increase the output of internal combustion engines, turbo-blowers of one to three stages are used, the driving power being supplied by an electric motor or by a turbine using the exhaust gases from the engine.

For blowing the water out of the diving tanks of submarines, small and light turbo-blowers are employed giving a pressure of 7 to 11 lbs. per sq. in. and driven by electric motors mostly through gearing.

In mines, shipbuilding yards and engineering works, large quantities of compressed air are used for coal cutters, rock drills, haulage, mine locomotives, hammers, drills, riveters and other pneumatic tools. Multi-stage turbo-compressors delivering upwards of 4,000 cu. ft. of air per minute for these purposes at pressures of 70 lbs. to 120 lbs. per sq. in. are found more economical than the reciprocating compressor. Such compressors may be provided with integral or separate dehumidifying plant of the turbo type described earlier in this article.

Similar multi-stage turbo-compressors are used for compression of gases in the manufacture of synthetic ammonia, in the hydrogenation of coal and in refrigerating plant of large outputs.

It will be obvious that such a variety of applications necessitates a large range of sizes having a normal volume at the inlet of from 1,200 cu. ft. per min. to 50,000 cu. ft. per min., the pressure range extending from 1¼ lbs. per sq. in. to 130 lbs. per sq. in.

In conclusion, it is apparent that the rapid commercial development of turbo-blowers and compressors has been due to their obvious advantages over other types of machines. The internal parts are not lubricated, hence not only is there a saving in lubricating oil, but the air or other gas being compressed is not polluted by oil vapour. There are no wearing parts except the bearings, and the cost of maintenance is thus exceptionally small. Their dimensions and weight, especially in the case of the larger machines, are smaller than those of corresponding machines of other types, and their cost and the cost of foundations in many cases much smaller. Their operation is quiet and efficient and they are suitable for direct drive by steam turbines, for direct or geared drive by electric motors, or geared drive by gas or oil engines.

Finally, it may be stated that turbo-blowers and turbo-compressors driven by steam turbines, electric motors and even internal combustion engines have conquered many fields which the reciprocating machine used to dominate. Being particularly suitable for dealing with large volumes of gas, they lend themselves to centralization and to the development of more economical industrial plant units.

Electric Arc Welding.

By E. C. DAVIES, A.M.I.E.E.
Design Dept., Witton Engineering Works.

The application of electric welding to industrial processes is continually making headway. As a result, many engineers are faced—often at short notice—with the need for acquiring some general idea of the main considerations governing welding technique.

In this article an endeavour is made to meet this need. The fundamental requirements necessary for efficient welding are investigated, and the salient features of modern welding equipment described.

INTRODUCTORY.

ELECTRIC arc welding has been introduced into all the more important branches of engineering both in this country and abroad. It is interesting, for example, to note its increasing application in the shipbuilding industry, in spite of the economic difficulties of the past few years and the special problems involved in such a complex structure as a ship's hull and superstructure. There are few shipbuilders or repairers who do not avail themselves to some extent of its proved advantages over riveting. It has been estimated, for instance, that a saving of approximately 4 per cent can be effected in the cost of constructing a medium sized cargo vessel by making full use of electric welding. An investigation of this nature brings to light some interesting indirect economies which can be obtained, such as the elimination of the comparatively inefficient air supply lines required to feed the pneumatic tools used in constructing a riveted ship.

In addition to cost considerations, the very valuable reduction in weight which is made possible by the adoption of a welded form of carefully considered design, as distinct from an attempt to reproduce the welded counterpart of a riveted construction, is an important factor in its favour.

Finally, the difficulty of obtaining and maintaining oil tightness in the riveted connections of tankers and the oil-fuel bunkers of other vessels is minimized by the use of welded joints, which have been found capable of withstanding successfully the severe stresses set up during heavy weather on the North Atlantic routes.

Progress in arc welding is also being made in the various branches of structural steelwork, for it is now being used extensively in bridge and steel-framed building fabrication. In those cases where it has been appreciated that radical changes in structural design are necessary in order to obtain the greatest benefit from the use of a welded construction, the results have been thoroughly satisfactory. Welding has also been largely responsible for the development of ferro-concrete type of composite structures for which the light steel trusses can be

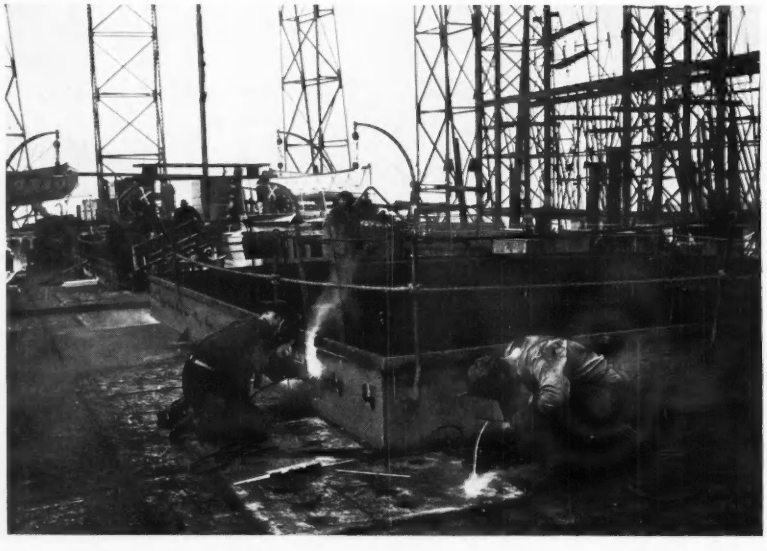


Fig. 1.—Typical welding operations in ship construction.

produced more efficiently by welding than by riveting.

Other prominent examples of the substitution of arc welding for riveting include the construction and repair of gas holders and petroleum tanks, and an increasing amount of work in connection with the construction and maintenance of rolling stock. In addition, weldings are to a great extent replacing castings in the heavy engineering industries and recent instances of arc welded pipelines indicate the invasion of yet another specialized field.

When it is appreciated that in spite of the progress which has been briefly outlined, the possibilities of arc welding have been only partially explored, it will be realized that electric arc welding is likely to become an exceedingly important factor in industry.

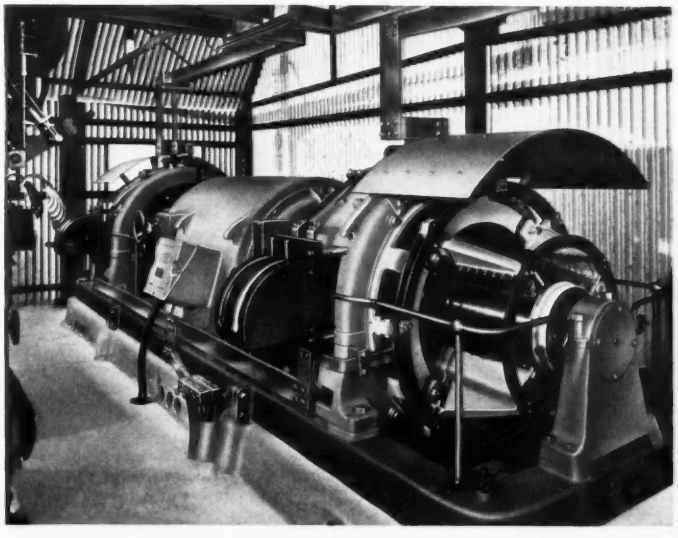


Fig. 3.—Two 2,000 ampere multi-operator welding generators installed in an important shipbuilding yard.

METALLURGICAL CONSIDERATIONS.

The subject is best approached by considering arc welding as a casting process, in which the arc forms a small scale electric furnace for the purpose of melting down the filler rod and a portion of the parent metal. Although it is obviously impracticable to expect the welding operative to possess a detailed knowledge of metallurgy, it is advisable that whenever possible the training of supervisors should include a study of the fundamentals governing the process of steel making. There are, however, essential differences between steel making phenomena and those occurring during arc welding. For instance, the temperature at which the metal is cast is much higher in the case of welding, and deposition is made in a cast-quenched condition. Also, since the weld metal is in a molten state for a few seconds only, the possible effect of any reactive agents which might be employed during this period must necessarily be minimized, whereas in the steel furnace, reactions between metal and slag play an essential part in the process and largely determine the ultimate composition of the metal.

Fig. 2.—Fillet welding of strengthening ribs to an oil circuit breaker tank.

The technique of the steel maker, therefore, is not applicable to arc welding processes without considerable modification.

Electrode Characteristics.

In order to obtain the necessary physical characteristics from the deposited metal, the first consideration should be the composition of the filler rod. Experience in this connection indicates that for the welding of low carbon steels the rod should be of a type of mild steel having the following chemical analysis :—

Carbon	0.1 to 0.15 per cent.
Manganese	0.3 to 0.5 per cent.
Sulphur, Phosphorus	Not more than 0.05 per cent.
Silicon	Trace.

"Rimming steel," so named because of its cooling characteristics exhibited in the ingot mould, conforms to the above analysis and is largely used for this purpose. The tensile strength required in the deposited state is in the region of 30 tons per sq. inch.

There now arises the problem of the protection of the deposit whilst fluid, in which state the metal

will readily take up carbon, oxygen and nitrogen, all of which are capable of seriously affecting the strength and ductility of the weld.

An examination of weld metal deposited by unprotected electrodes reveals the presence of nitrogen in the form of (a) iron nitride (Fe_4N), which when viewed under a magnification of 500 or more diameters appears as a series of needle-like deposits, and (b) the eutectoid form known as braunite, having a lamellar structure. The effect on the physical properties of the metal is to cause excessive brittleness, which, owing to subsequent precipitation or solution, may only become apparent during service and is therefore particularly undesirable on this account.

The oxides also produced are usually found at the crystal boundaries, and having negligible tensile strength, seriously weaken the weld.

Although until comparatively recently bare wire welding was used extensively, particularly in the United States, it is recognized today that where reliable results are essential some protection must be provided for the molten metal during the critical period. The protection must take the form mainly

Fig. 4.—Typical coated electrode with portion of the covering removed to show the formation of the protecting sleeve around the core.

of a blanket or screen capable of excluding the undesirable elements for the short period during which the metal remains fluid. There are many methods of accomplishing this, of which the following are the more usual :—

1. *External Gas Screen.*

This may be provided by directing into the arc zone a stream of an inert or reducing gas such as carbon dioxide or hydrogen which is drawn from suitable containers. Owing to the inconvenience of attending to gas valves while manipulating the electrode, this method is almost entirely confined to certain types of automatic plant working on comparatively long seams, and the special case of the atomic-hydrogen torch, in which the hydrogen is atomized in the arc and, recombining in the vicinity of the weld, liberates in the form of heat, the energy absorbed during dissociation.

2. *Powdered Flux Applied to the Work Before or During Welding.*

Although this method is sometimes adopted with certain classes of work, it is not in general use, partly owing to the inconvenience involved, but mainly due to the fact that during the important period whilst the metal is being transferred from the electrode to the work it is only partly protected and is liable to become contaminated before gaining the protection of the fused flux pool.

3. *By Separately Feeding Cellulose into the Arc Zone.*

On certain types of automatic welding machines using bare wire, an attempt is made to create a reducing atmosphere by feeding a cellulose substance into the vicinity of the arc, where it absorbs oxygen by combustion. The material is generally made up in the form of a rope, and the feeding mechanism is operated by a small motor which may also drive the electrode wire feed.

4. *By a Coating on the Electrode.*

This is the method used for most manual welding operations, but it presents certain problems in connection with automatic work employing continuous electrodes, owing to the difficulty of conducting the current to the metal core.

Many different commercial brands of covered electrodes are now available, each claiming some special characteristic, but in the main, the coating is designed to perform one or more of the following functions.

(*a*). To fuse at the arc temperature and form a fluid slag, the specific gravity of which is sufficiently low to enable it to rise through the pool of deposited metal and form a protective layer above.

The slag so formed serves the double purpose of prolonging the period during which the metal remains fluid, thus allowing more time for any trapped slag or gas to escape, and also of excluding atmospheric oxygen and nitrogen by blanketing the deposit and in some degree by coating the drops of metal during their transfer from the electrode to the work.

Iron oxide and silica or asbestos are chiefly used in this type of covering.

(*b*). To produce at the arc temperature a supply of gas in sufficient quantity to form a protecting envelope around the molten metal. Such coatings contain an organic constituent, usually some form of

cellulose, which at this temperature decomposes and liberates carbon monoxide and hydrogen. These gases, which have excellent reducing properties, tend to limit the quantity of atmospheric oxygen in the vicinity of the weld. The volume of gas liberated must be sufficient to provide a blanketing effect in the critical zone, and so exclude atmospheric nitrogen.

(*c*). To fuse at such a rate relative to the metallic core that a projecting sleeve is formed, as shown in fig. 4, which gives additional protection to the metal being transferred from electrode to work.

The ideal electrode covering is one which combines the characteristics of protection by gas screening and by the formation of a slag which can readily be removed. There is always the danger where the slag clings excessively to the weld, that the operator may neglect to remove obstinate portions before he starts to deposit a second layer of metal, with the result that they become trapped in the weld. This point is of importance, as slag inclusions are fruitful sources of fracture.

The Process of Transfer.

It is now necessary to examine the manner in which the metal is actually deposited. Owing to the nature of the arc, and the need for protecting the eyes of the operator from damage by interposing a dense screen between his eyes and the work, direct optical observation of the process leaves the investigator with a very limited impression of what actually takes place. However, as the result of a number of experiments conducted mostly on the Continent and in the United States, some interesting information regarding transfer phenomena has been obtained.

The method adopted by Creedy in the United States consisted in projecting an enlarged image of the arc on to a screen, and reducing the current intensity, and consequently the rate of transfer, sufficiently to enable the process to be followed. Better results obtained at more normal welding currents were secured in Germany and elsewhere by employing high-speed cinematography, the number of pictures taken per second being in one case as high as 4,000. More recently, Sack has described experiments conducted in Holland with a radio-cinematograph apparatus using X-ray films. This method has the advantage of differentiating between the images produced by the electrode core and those of the covering, the former being denser and easily distinguishable.

As the result of this work, it is now established that the transfer of metal from rod to plate takes at least two distinct forms. The first of these consists in the growth of small globules of metal, which, whilst still quite small are parted from the electrode and pass across the arc gap to the plate. In suitable electrodes these drops may be developed completely within the sleeve of the coating. Radiographic records of the drops transferred from these electrodes prove that they are surrounded during the whole of this period by a layer of molten slag.

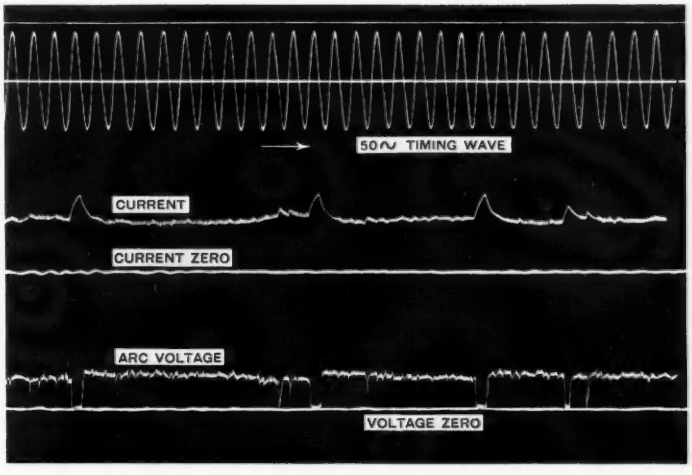


Fig. 5.—Oscillogram from drooping characteristic D.C. welding set.

From time to time, however, a drop is formed which continues to grow until it completely bridges the gap between the rod and the pool of metal. It will be appreciated that considerable disturbance is caused in the electrical circuit supplying power to the arc by the passage of these drops, particularly the larger drops which cause momentary short circuits. Oscillograms indicating current and arc voltage during a welding operation clearly illustrate this effect. In the typical record shown in fig. 5, the transfer of the larger drops result in periodic short circuits, indicated by zero potential and increased current between the electrode and work. In addition to these comparatively long periods, there is also a number of occasions during which the arc voltage is momentarily reduced by the passage of the small drops which takes place without actually short circuiting the arc.

Further fluctuations in the electrical circuit occur as the result of unavoidable variations in the length of an arc maintained by hand. Automatic welding by controlling the arc length electrically eliminates this difficulty.

ELECTRICAL CONSIDERATIONS.

The Effect of Supply Characteristics.

It has already been suggested that a welder is actually controlling a miniature casting process, so that every effort should be made to ensure a correct

and uniform flow of heat in order to secure reliable results. A considerable contribution in this direction can be made by employing a source of welding power having the correct characteristics.

Direct Current Welding.

A direct current supply must first provide ample voltage for striking the arc from a metal surface which is usually oxidized. Secondly, the current peak resulting from the initial contact between the

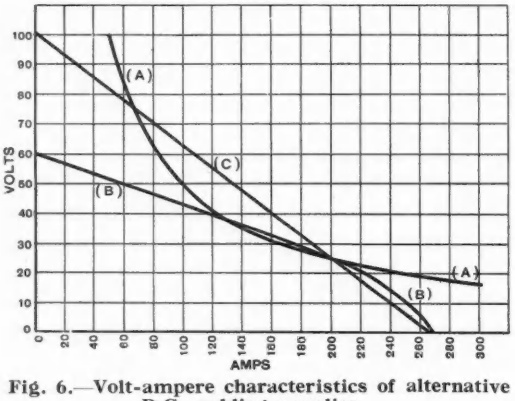


Fig. 6.—Volt-ampere characteristics of alternative D.C. welding supplies.

electrode and work must not be high enough to cause the tip of the electrode to heat up rapidly and stick or "freeze" to the work before the operator is able to draw an arc.

Immediately after ignition the applied voltage must fall to a value determined by the arc characteristics which conform to the following general formula :—

$$V = a + bi$$

when V = Voltage across the arc.

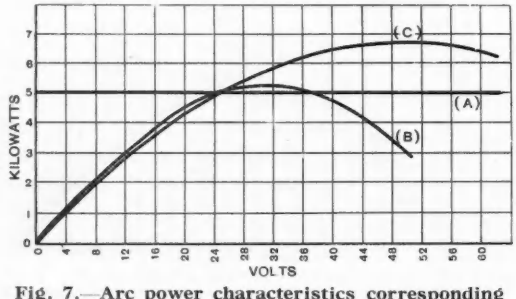


Fig. 7.—Arc power characteristics corresponding to fig. 6.

a and b are constants depending on :—

1. The arc length.
2. The composition of electrode core.
3. The thickness and nature of the coating.

i = Instantaneous arc current.

The terminals of the welding supply may therefore be regarded as being connected to a load, the effective resistance of which fluctuates between wide limits as the arc length is changed by the relatively slow movements of the operator's hand and by the almost instantaneous short circuits and partial short circuits caused by the passage of the metallic drops.

In the intervals between the transfer of the larger drops, neglecting for the moment the effect of any reaction due to the constituents of the coating, the arc supplies the heat energy which is distributed in the ratio of 67 per cent at the positive and 33 per cent at the negative poles. If the volt-ampere characteristic of the supply follows the hyperbolic curve indicated as (A) in fig. 6, the electrical power and therefore the flow of heat will be constant irrespective of any changes in voltage due to alterations in arc length.

At the moment of short circuit, however, the heating effect is produced by the passage of current through the molten drop and is therefore concentrated in a smaller zone. With a supply characteristic approaching the (A) curve, since the voltage is small the arc gap now bridged by the drop across the resulting current would be many times that flowing during the uninterrupted arc periods, and the heat produced within the globule would cause a rapid increase in temperature accompanied by abnormal turbulence. The flow of deposit in these circumstances would be difficult to control due to excessive "spatter," there would be a tendency for slag to become trapped in the metal, seriously impairing the strength of the weld.

The ideal volt-ampere characteristic of a welding supply therefore is one which, over a small range of pressure above and below the average arc voltage, ensures a substantially constant supply of power, and therefore heat, to the arc, but which also limits the maximum possible current during the short circuited periods to between 120 per cent and 150 per cent of the average value, depending on the class of work undertaken. Characteristic curves of this type are shown in fig. 6 (B) and fig. 7 (B).

For thin sheet metal work it becomes particularly desirable to limit these current peaks, which if large may puncture the material. It must also be understood that the characteristic referred to, is that which results from extremely rapid changes in effective load resistance, and is not necessarily identical with the volt-ampere curve obtained under steady conditions. The relation between the static and dynamic characteristics is determined by the equivalent inductance effect of the complete supply circuit.

It was common practice in the early days of welding by direct current to take the power from a supply having a constant potential of 100 volts. A resistance was then inserted in each welding circuit, with the result that a straight line volt drop characteristic, denoted by (C) in fig. 6, was obtained across the arc. The corresponding curve showing the power absorbed in the arc is given in fig. 7(C). This arrangement conformed to the requirement of

limited current peak, and owing to the absence of inductance in the welding circuit, the static and dynamic characteristics were identical. The serious objections, however, were first, that approximately 75 per cent of the total power consumed was wasted in the resistance, and secondly that the power available at the higher voltages enabled the arc to be maintained at abnormal lengths, with the corresponding added risk of atmospheric contamination in unskilled hands.

Welding from a constant voltage supply is still a most convenient solution to the power problem when a number of points have to be fed simultaneously, but the amount of power wasted in resistances is now reduced to 45 per cent, or less, by employing a pressure of 40—50 V. instead of 100 V. The use of resistance only in the arc circuit produces the static characteristic (A) in fig. 8, which, it will be noticed, does not conform to the ideal curve previously described. However, the provision of a suitable reactance unit in series with each resistance, has the effect of producing a dynamic characteristic such as that denoted by curve (B), due to the additional induced voltage which is proportional to the rate of change of the arc current. The function of the reactance is therefore to ensure an approximation to the ideal characteristic by limiting the rate of change of current due to the changes in effective arc resistance under working conditions. Data obtained from oscillograms taken during typical welding operations provide information on which the design of an efficient choke unit may be based.

The oscillogram reproduced in fig. 9 illustrates the ratio of current change to voltage induced in a reactance designed for this duty.

Drooping Characteristic Dynamos.

Direct current generators intended for the supply of power to single welding circuits, are usually of the so called drooping characteristic type, having volt-ampere characteristics generally similar to the (B) curves of figs. 6 and 7. Such machines are incapable of supplying more than one arc at a time, since the volt-ampere demands of two or more simultaneous arcs cannot possibly coincide.

The chief advantage of this class of welding generator over the constant potential machine, lies in the elimination of the resistance losses associated with the latter. Owing also to the consequent improvement in efficiency, the capacity of the driving unit may be reduced considerably—an important advantage when portability is a desirable feature.

There are many forms of single-operator direct current generators on the market in which are incorporated widely differing design features, the majority of these being directed towards securing improvements in the characteristics under rapidly changing load conditions. The ideal static volt-ampere curve can be obtained without difficulty by employing a combination of shunt and reverse compound excitation, but owing to the magnetic

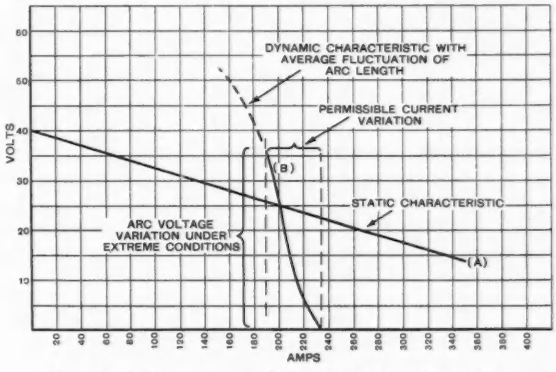


Fig. 8.—Volt-ampere characteristics of welding supply with stabilizing reactance.

inertia of the field system, the dynamic characteristic, or "response," of an ordinary generator so constructed leaves much to be desired. When this type of machine is employed for welding duty, reactances are usually provided to improve the performance.

Most modern single-operator welding dynamos, however, employ some special system of excitation which eliminates or greatly reduces this sluggishness, making the dynamic and static characteristics more nearly coincident. The Rosenberg, or "cross-field," principle using series excitation only, and various forms of magnetic shunting are frequently employed to attain this end.

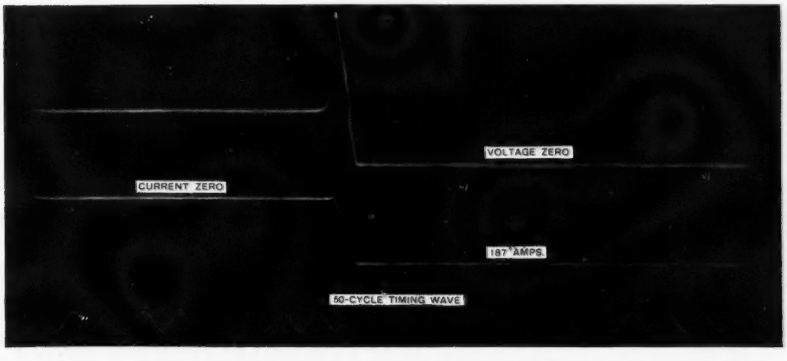


Fig. 9.—Voltage induced in welding reactance when normal current is interrupted.

The practical indications that a welding set is satisfactory are :—

1. That the arc is easily struck without "freezing."

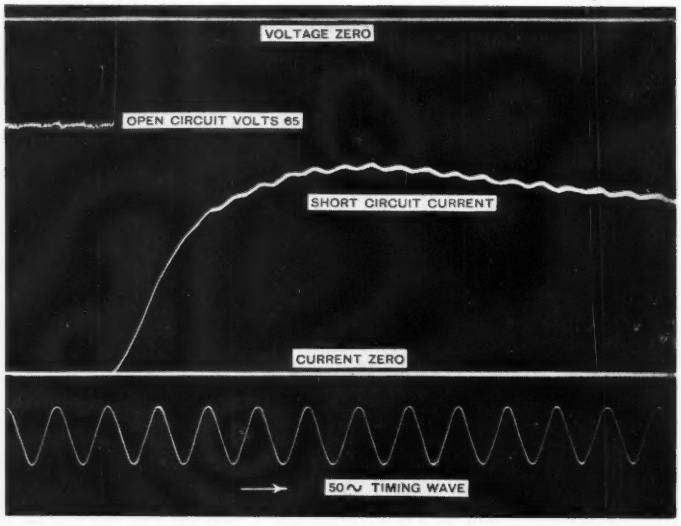


Fig. 10.—Oscillogram of sudden short circuit taken on a drooping characteristic D.C. welding set.

2. That the arc is easily maintained, there being no tendency towards frequent "snapping out."
3. That the metal flows smoothly, and—together with the slag—is easily controlled without "spatter."
4. That uniform results are obtained throughout the length of a weld.

The readings of meters connected in the welding circuit provide an additional means of checking performance. When used by an operator of average skill the current taken should remain reasonably steady under conditions of rapid voltage fluctuation.

The response characteristics of a typical stabilized drooping characteristic generator are recorded on the oscillograms shown in figs. 10, 11 and 12.

Alternating Current Welding.

The use of alternating current at normal supply periodicity for arc welding introduces additional factors which are worthy of consideration.

Referring to figs. 13 and 14, it will be seen that the current wave form is approximately sinusoidal, and is in phase with the arc voltage. The resulting power supplied to the arc which is of course extinguished at each half cycle, alternates between a maximum and zero at twice the supply frequency, and the ideal of constant heat flow to the arc is consequently impossible.

Early experiments with alternating current arc welding were disappointing, and using the bare or lightly coated rods which were available at the time, it was found that the arc was so difficult to maintain that the process was generally regarded as being unsuitable for work of any importance. Subsequent investigation, however, resulted in modifications which have improved the performance to such an extent that welding by alternating current is now as reliable as that employing direct current, and is even to be preferred for certain classes of work.

The first step towards attaining this end, was the inclusion of a correctly designed choke unit in series with the arc, power being supplied from a suitable transformer. The effect of this is indicated in fig. 13,

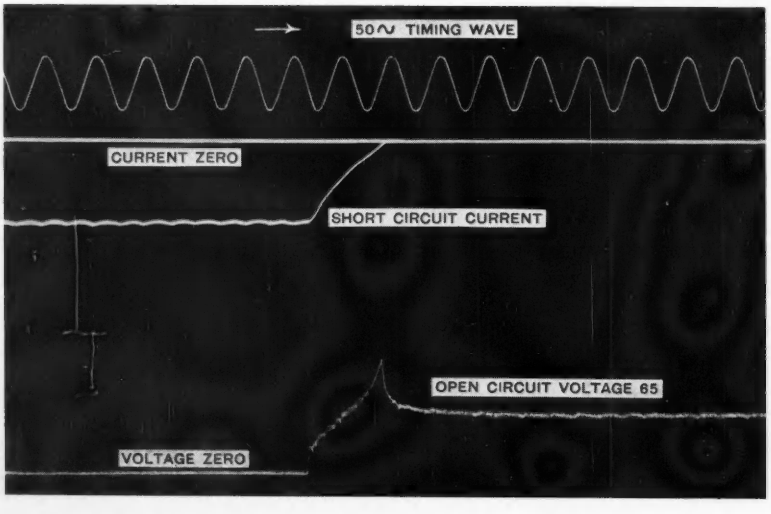


Fig. 11.—Voltage rise on sudden open circuit. Oscillogram taken on drooping characteristic D.C. welding set.

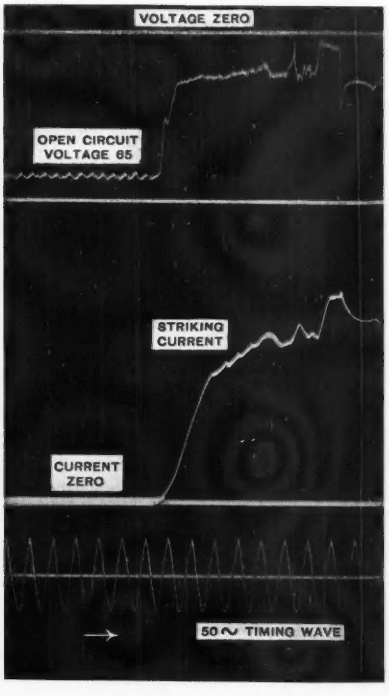


Fig. 12.—Current rise when striking arc, (drooping characteristic set).

in which it will be seen that the phase displacement brought about by the self inductance of the choke ensures that the welding current and the transformer secondary voltage cannot pass through their zero value at the same instant. As a result, at the instant of zero current, when the arc is extinguished, the transformer voltage available for restriking the arc is high enough to ensure instant re-ignition. The actual amplitude of the voltage curve at this point is controlled by the value of the self inductance of the choke coil, which determines the phase displacement and power factor of the apparatus. It is therefore clear that in order to obtain arc stability, which depends upon regular and instant re-ignition at the end of every half cycle, the natural power factor of the combination of transformer and choke must necessarily be low, and in practice usually lies between 0.25 and 0.4.

At this point it may be of interest to examine the effect of substituting a resistance for the choke unit, the corresponding curves for such an arrangement being shown in figs. 15 and 16.

The arc voltage and current and the transformer secondary voltage are now in phase with each other, and owing to this fact, there occurs an appreciable interval between the extinguishing of the arc at the end of one half cycle, and the instant of re-ignition at the beginning of the next. This effect is cumulative by reason of the fact that any delay in restriking results in a de-ionization of the arc zone, and since the effective resistance of the arc path is inversely proportional to the degree of ionization present, the voltage necessary for restriking becomes proportionately higher as the zero current interval is prolonged. Also, the higher the striking voltage, the longer must be the interval before the transformer voltage reaches this value.

The corresponding power curves, as will be seen in fig. 16, are obviously unsatisfactory from a welding point of view, the additional interruption of the power flow to the arc resulting in excessive instability and undesirable changes in temperature of the molten metal. In fact, resistance stabilization of alternating current arcs is only practicable when special measures are adopted for continuing the ionization during the unavoidable zero current periods.

The current wave form may be determined from the following theoretical considerations which also enable the voltage induced in the choke coil to be calculated.

Assuming that the voltage across the arc conforms approximately to the law

$$e = a + bi,$$

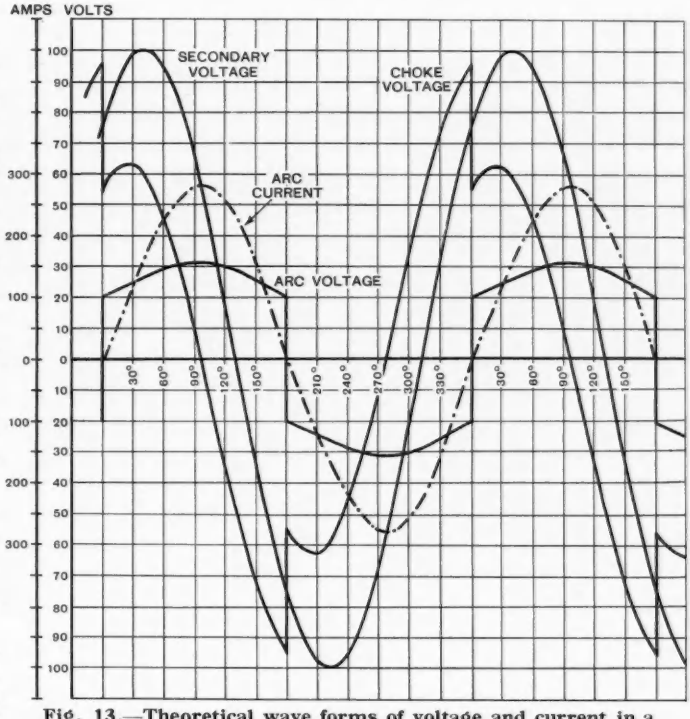


Fig. 13.—Theoretical wave forms of voltage and current in a welding transformer with choke stabilization of arc.

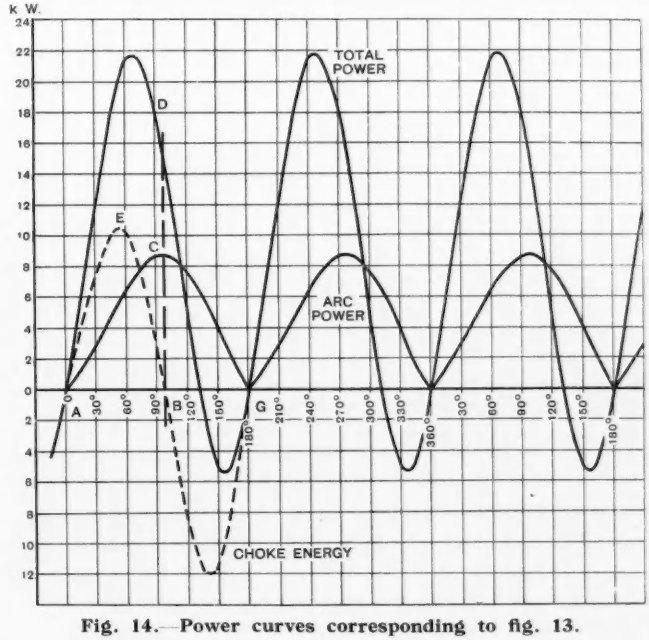


Fig. 14.—Power curves corresponding to fig. 13.

where e = Instantaneous arc voltage
i = ,, ,, current
b = A constant
a = A constant having alternately positive and negative values

then the amplitude of the transformer secondary voltage at any instant will be equal to the sum of the arc voltage, the resistance drop, and the voltage

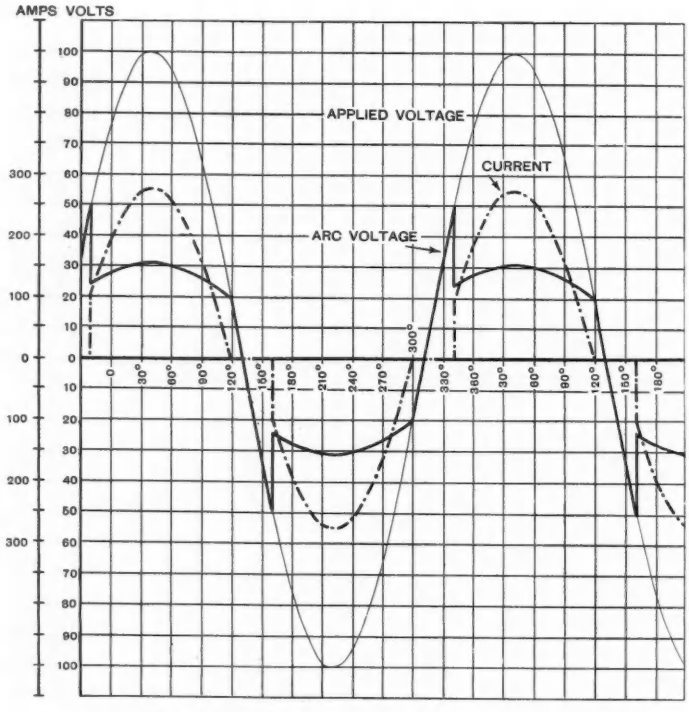


Fig. 15.—Theoretical wave forms of voltage and current in a welding transformer : resistance in series with arc.

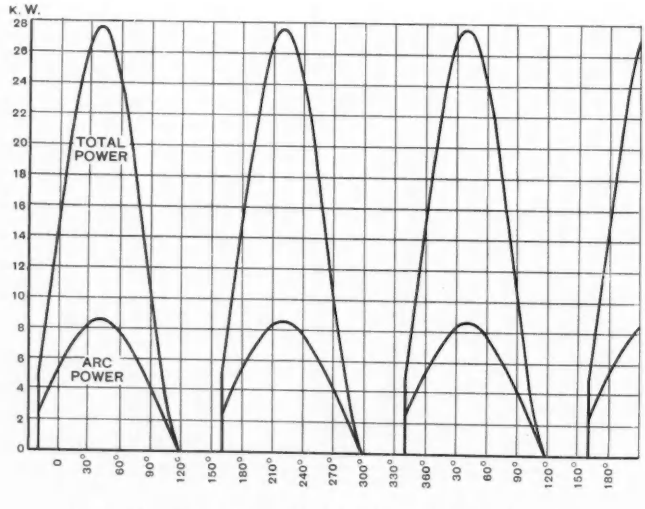


Fig. 16.—Power curves corresponding to fig. 15.

induced in the choke. Assuming a sinusoidal secondary voltage wave, this may be expressed—

$$\hat{E} \sin (\omega t + \phi) = L \frac{di}{dt} + ri + a + bi$$

where—

$\hat{E}$ =maximum voltage of transformer secondary winding at the corresponding load.

L =Coefficient of self induction of choke unit.

ϕ =Phase angle between voltage and current at the zero values.

r =Resistance of choke unit.

Solving for i, and assuming empirical values for a and b, the current wave form and the choke voltage curve may be plotted as shown in fig. 13. These approximate fairly closely to the average results obtained in practice as will be seen by referring to the oscillograph record in fig. 17. Similarly, the curves illustrating the case in which a resistance was substituted for the choke coil were obtained from the expression :—

$$\hat{E} \sin \omega t = r_1 i + a + bi$$

where r_1 = Ohmic value of the resistance unit.

Referring to the energy curves given in fig. 14, it will be noticed that during the period A to B, the power absorbed in the arc represented by the area ACB is considerably less than the total energy in the circuit ADCB, the difference representing the amount which is stored magnetically in the choke coil AEB. Neglecting losses, this latter is all returned during the ensuing period B to G and maintains the arc, the current of which continues to flow in the same direction, whilst the transformer secondary voltage falls to zero and finally reverses in polarity.

The addition of the correct value of self induction to the arc circuit, however, did not entirely solve the problem. Even under the improved conditions, the flow of power to the arc, as will be seen in fig. 14, although uninterrupted by prolonged zero periods, was necessarily alternating in character, and when used in conjunction with bare or lightly covered electrodes produced results that could not be compared with those obtained with direct current apparatus.

Within the last few years the introduction of the heavier coated electrode has been instrumental in placing the welding transformer on a par with direct current plant for most normal operations.

The effect of the coating is twofold. First, the mantle of molten slag which it produces, acts as a heat insulator, conserving the thermal energy supplied to the welding zone during the period in which the power delivered to the arc falls below the ideal level.

Secondly, the constituents of the coating are such that ionization is encouraged during periods of low power, and greatly improved arc stabilization results.

Alternating current welding has a number of advantages over direct current work. For instance, the magnetic or "blow effect" associated with the direct current arc, particularly on heavier currents, is minimized when using alternating current at normal periodicities. Another advantage often claimed, is that the nature of the power supply to the weld necessitates the maintenance on the part of the operator of a short arc, with the corresponding reduced possibility of atmospheric contamination of the molten metal, during its transfer from electrode to work.

The advantages of the welding transformer from the point of view of low initial cost, and the negligible amount of upkeep resulting from the elimination of all rotating parts are well known, and are largely responsible for the growing demand for this type of plant.

Although it has been proved that the inherent power factor must be low, comparisons with direct current plant driven by induction motors are often unfair, inasmuch as they generally ignore the fact that the latter are usually running for a considerable period of the day on a very much reduced load, during which time the power factor may often fall as low as 0.2.

Where it is essential to improve the power factor of a static welding equipment, it is usual to include a suitable bank of condensers.

Connections of Single and Multi-operated Transformers.

Welding transformers must be constructed with independent primary and secondary windings, the auto-transformer type being unsuitable on account of the increased possibility of shock to the operator.

The simplest form of single-operator plant consists of a transformer having single phase primary and secondary windings. Most public power supplies, however, are three phase, and the use of a single phase unit on such a system results in unbalanced loading of the three lines. In an attempt to avoid this, specially connected 3 : 1 phase transformers are sometimes offered as a solution. The following table compares the current distribution of a typical example of this type of apparatus having its secondary winding connected open-delta, with that obtained by connecting an equivalent single phase unit across two lines of the three phase supply.

Type of Transformer.	Line Current.		
	A	B	C
Single phase transformer	1.0	1.0	0.0
3 : 1 phase transformer	1.16	0.58	0.58

Thus, it will be seen that although the specially connected transformer provides a better balance of load across the three phases, the internal power factor is lower than that of the single phase set, and results in an increased loading on one line of 16 per cent. Since the limit of supply loading is reached when one cable is fully loaded, the 3 : 1 phase transformer offers no advantage in this respect. When the further disadvantages of this latter type are considered, such as its additional cost, lower efficiency and the increased difficulty of providing for power factor correction, there appears to be no doubt that the single phase transformer is to be preferred. The final choice, however, often lies with the supply authorities, who sometimes insist on the installation of 3 : 1 phase units.

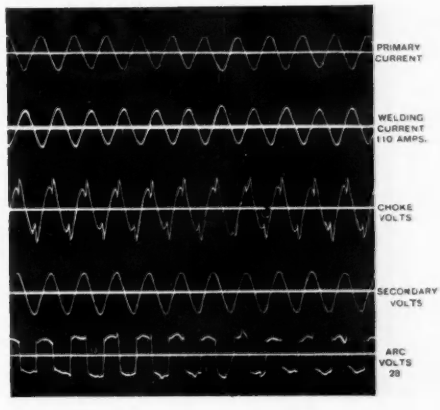


Fig. 17.—Characteristic voltage and current wave forms from a single-operator welding transformer with choke stabilization.

Double operator sets are usually wound either single phase or 3 : 1 phase. By the provision of a simple switching arrangement the two output circuits may be used independently, or may be paralleled, to provide for occasional heavy duty demanding double the normal output of each circuit. Thus a 200 amp. double-operator welder may be used also as a single-operator set for 400 amps.

Transformers required to supply three or more welding circuits are usually provided with three phase windings on both primary and secondary, the welding circuits being connected between the three secondary phases and the star point of the transformer which is earthed.

In order to obtain a reasonable degree of phase balance on a three phase multi-operator installation, some care has to be exercised in the distribution of the various operations, but it is usually possible to ensure that at least the major portion of the load is divided equally between the three main circuits.

Interference between operators supplied by the same transformer is possible on badly designed equipment, and may affect the quality of the work produced to a serious extent. This can be avoided

by correctly proportioning the essential components, and further assistance in this direction can be obtained by the interconnection of the secondary windings as indicated in fig. 18. The choke units, one of which is required for each welder, must be provided with means for varying the current output in small increments, this being accomplished either by varying the number of effective turns in the coils by means of a tapping switch, or by altering the reluctance of the magnetic circuit by some convenient mechanical operation. They should also be made as portable as possible so that they may be readily accessible to the operator who may be required to work over a considerable area.

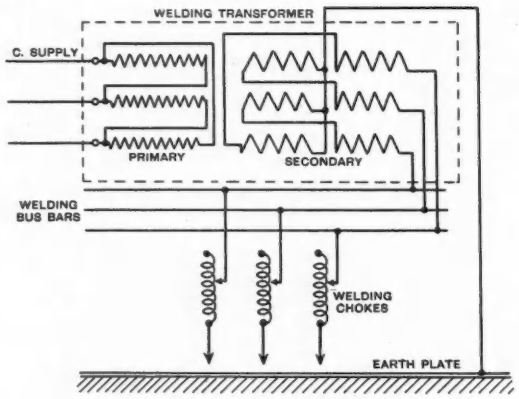


Fig. 18.—Multi-operator transformer with interconnected secondary.

AVAILABLE METHODS OF TESTING.

The preceding notes have been devoted to outlining the basic principles of arc welding and the major functions of the apparatus involved. As a discussion involving the various forms of actual welded connections and questions of technique is outside the scope of this article, it is proposed that final considerations should be confined to a brief examination of the available methods of testing.

Destructive Tests.

The primary object of destructive tests is to determine the suitability of materials proposed for a particular duty. British Standard Specification No. 538 describes in detail suitable methods of preparing test specimens of weld metal in the deposited state for the purpose of carrying out tensile and notched bar impact tests. Satisfactory results obtained from these constitute the first steps towards ensuring reliable work by avoiding failure due to the use of unsuitable electrode material.

Mechanical tests may also be taken on samples of representative welded connections, sometimes specified as being obtained from extensions attached to the main body of the article to be produced and welded as a continuation of a principal seam. Definite methods of carrying out these tests are also specified in British Standard Specification No. 538, which legislates for tensile tests on butt and fillet welded specimens, and bend tests on butt welds.

Useful data may also be obtained by exploring the immediate vicinity of the weld with a Brinell ball or diamond-point hardness tester, since a close relationship exists between the surface hardness and the behaviour of a weld under stress.

In addition to the above, optical or microscopical examination of suitable sections of welded samples is sometimes resorted to, and under skilled direction is capable of conveying valuable information. Specimens for this purpose are prepared by careful grinding and polishing, after which they have to be treated with a suitable etching re-agent in order to obtain photographic contrast between the constituents to be examined. Magnifications of 150 to 250 are usually employed for these investigations, but as has already been stated, it is necessary to extend this beyond 400 in order to examine for possible nitride effects. Fig. 19 illustrates a typical example of fillet welding in the final etched condition, in which the boundaries of the area disturbed by heat are clearly visible. Photo-micrographs taken at successive points, starting from parent metal and continuing through the junction to the outside edge of the weld metal are shown in fig. 20, a to f.

Preliminary tests such as these, while being useful, should be supplemented by careful inspection during work on the main body of the article, which should include methods of routine procedure calculated to ensure uniform results.

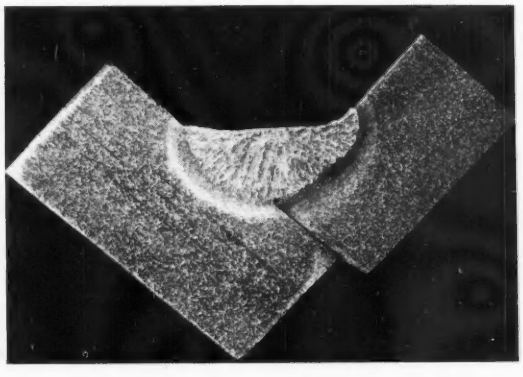


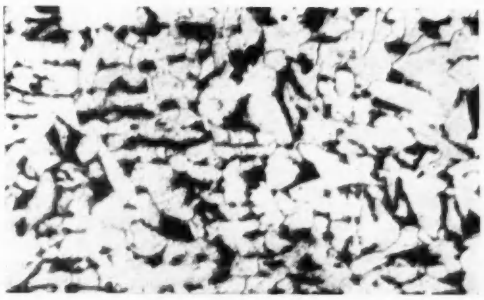
Fig. 19.—Macrograph of fillet weld. Single run deposit.

Non-destructive Tests.

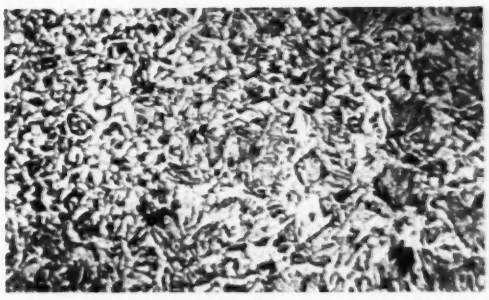
After welding, further information regarding the properties of the finished seams may be gained by inspection, with or without the aid of various types of testing apparatus. Although not conclusive, there can be no doubt that a very good

estimate of the condition of a welded connection can be obtained from its appearance only. An unsatisfactory weld will often present a form of contour which, together with the nature of its surface, will offer to the experienced inspector sufficient evidence for rejection. Final inspection can, however, be assisted to a considerable extent by utilizing testing apparatus operating on acoustic, magnetic or electrical principles.

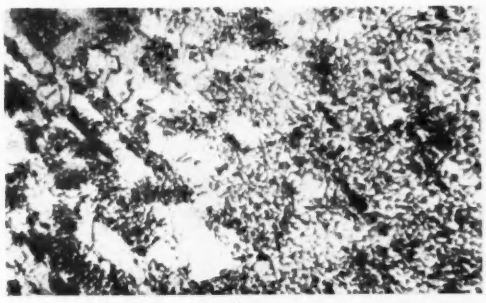
Magnetic fault detecting can be employed on suitable work, and is based on the principle that in the vicinity of a discontinuity in a magnetic circuit, the lines of force comprising the field are diverted and tend to escape beyond the confines of the metal body, this leakage being made apparent by suitable use of small iron particles. In one form, the work is magnetized progressively by



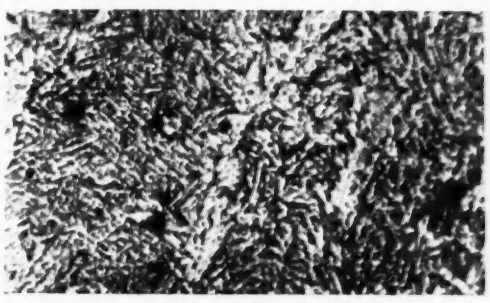
a.
Parent metal, showing typical forged structure.



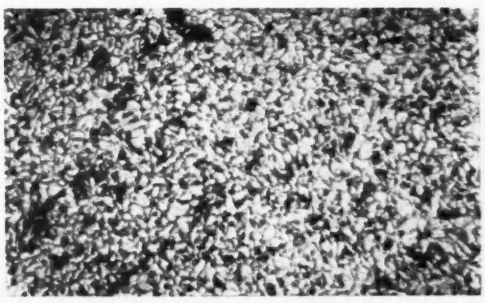
d.
Junction of parent and weld metal.



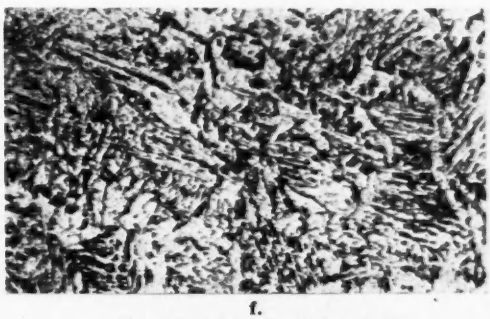
b.
Parent metal, commencement of heat refining (normalizing) due to welding operations.



e.
Centre of weld metal.



c.
Parent metal, completely normalized.



f.
Outside edge of weld metal.

Fig. 20.—Six micrographs taken across fillet weld metal of fig. 19 (magnification 150 diameters).

Acoustical examination is convenient in that the only instrument needed is some form of stethoscope. The procedure followed is to apply the transmitting end of the tube to the work, which is then struck sharply. With a little experience it is possible by this test to differentiate between sounds transmitted through homogeneous material and those passing across cracks or other evidences of faulty fusion.

Magnetic fault detecting can be employed on suitable work, and is based on the principle that in the vicinity of a discontinuity in a magnetic circuit, the lines of force comprising the field are diverted and tend to escape beyond the confines of the metal body, this leakage being made apparent by suitable use of small iron particles. In one form, the work is magnetized progressively by means of an electromagnet controlled by a sliding rheostat and the area to be inspected is washed with a solution containing very finely divided iron in suspension. Cracks or voids on or near the surface being tested are indicated by the formation of dense shadows on the wet surface, caused by the magnetic congregation of the minute iron particles.

There are a number of other methods of fault testing, such, for example as the passing of a fairly heavy current through the weld and exploring for areas of high resistance by measuring voltage drop at intervals. The chief criticism of all the foregoing methods of test, is the fact that none offers a means of detecting all the possible faults in a weld.

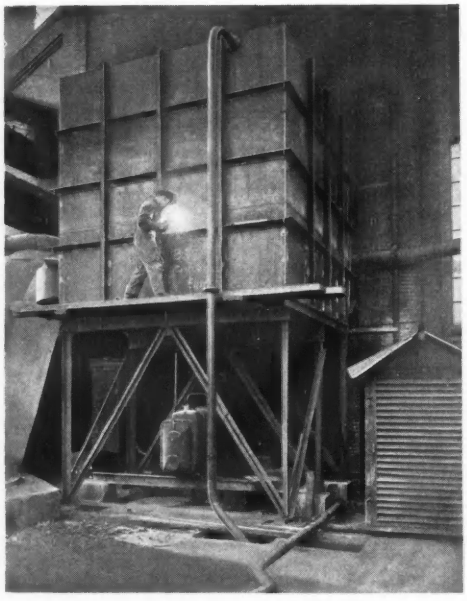
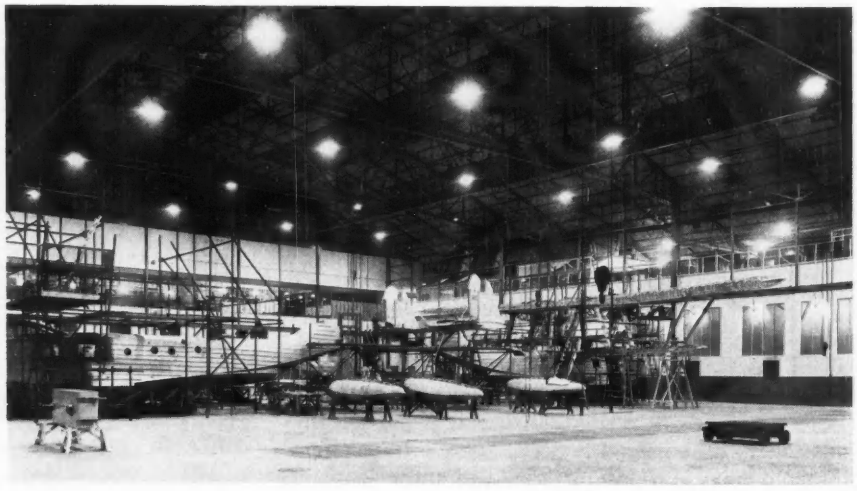


Fig. 21.—Arc welded steel storage tank.

For certain classes of work the installation of X-Ray apparatus has been considered a justifiable expenditure in the endeavour to eliminate all faulty work. X-rays during their passage through a material are partially absorbed, the amount of absorption being governed by the thickness and atomic weight of the substance. If it is possible, therefore, to place the X-ray tube on one side of the weld and a sensitized plate on the other, a photograph can be obtained which, for a material of uniform thickness, will indicate by an image of varying intensity the presence of areas lacking in homogeneity. Difficulties arising from changes in section occurring in a particular object, may be overcome by temporarily adding strips of metal of similar density to reinforce the thinner sections. In order to avoid overlooking faults occurring in a plane unfavourable to this method of detection, it is necessary to take radiographs from several angles, which also makes it possible to determine the shape and exact location of the defect.

It should not be inferred from the foregoing remarks on testing that an elaborate array of apparatus is necessary to take advantage of the potentialities of fabrication by arc welding. Sufficient practical experience has now been gained to prove that given suitable materials, properly trained operators, and a reasonable amount of supervision, which are the minimum requirements for first class results in most undertakings, all normal welding operations may be carried out with confidence. The more complicated testing methods may be reserved for work on heavily stressed members, or for circumstances which demand a particularly high factor of safety.

"Osira" Lighting in an Aeroplane Factory.



The Saunders Roe Aeroplane Erection Shed at East Cowes illuminated by 400 watt "Osira" lamps.

Voltage Regulation of A.C. Transmission and Distribution Systems.

PART II.—DESIGN OF REGULATING APPARATUS.

By C. H. NUNN, A.M.I.E.E.

Chief Designer, Transformer Dept., Witton Engineering Works.

Part I. of this article, which appeared in the G.E.C. Journal, Vol. VI., No. 3, p. 138, discussed the voltage regulation problem of a typical transmission and distribution system, and reference was made to the provision for regulating apparatus at various points.

The present article, while dealing with certain problems of regulation, outlines the general design of the actual regulating equipment and gives examples of apparatus available for the duty required.

GENERAL.

THE method of voltage regulation generally adopted both in this country and abroad is the application of a tap changer to either the primary or secondary of a transformer installed for the purpose of altering the system voltage ratio.

If, however, the transformer required for altering the system voltage ratio is already in existence without a tap changer, it is usually not an economic proposition to rewind it so that it is suitable for a tap changer. The normal method is to connect a booster in the system, the voltage of which is adjusted by means of a tap changer.

Tap changers are suitable for application to the largest transformers down to sizes of, say, 200 kVA. Below this size distributor boosters and other methods of regulation are frequently cheaper.

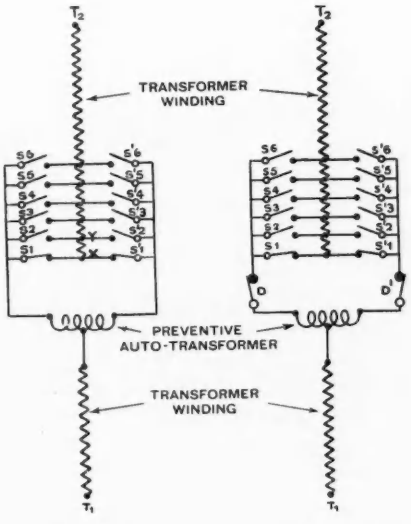


Fig. 16. Fig. 17.

Electrical circuits for tap changers (one phase only).

TAP CHANGERS.

The tap changers made in this country are generally designed to operate the electrical circuit given in figs. 16 and 17, or modifications thereof, some of the applications to three phase windings being given in fig. 18. It will be noted that tappings on a high voltage winding are taken from the centre of the phase in order to keep them as free as possible from the effects of line voltage surges and, in the case of large transformers, to reduce to a minimum the mechanical stresses set up by the uneven distribution of the ampere-turns along the winding, when turns are cut out by the tap changer.

The tap change cycle of one phase only of a transformer will be considered, as all phases simultaneously function in a similar manner, their operating mechanisms being mechanically coupled.

Electrical Tap Change Cycle.

In the position of the tap changer given in fig. 16, the transformer winding has all its turns in circuit. Starting from T_1 the current flows to the centre point of the 1/1 auto-transformer, where it

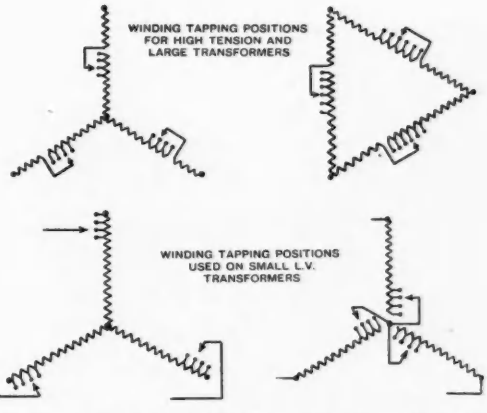

WINDING TAPPING POSITIONS FOR HIGH TENSION AND LARGE TRANSFORMERS
WINDING TAPPING POSITIONS USED ON SMALL L.V. TRANSFORMERS

Fig. 18.—Common methods of application of tappings to three phase transformers.

divides equally through the two halves and enters the transformer winding again *via* the switches S_1 and S'_1, and thence out to the line terminal T_2.

In order to alter the ratio of transformation one step, switch S_1 is opened, thus diverting the current

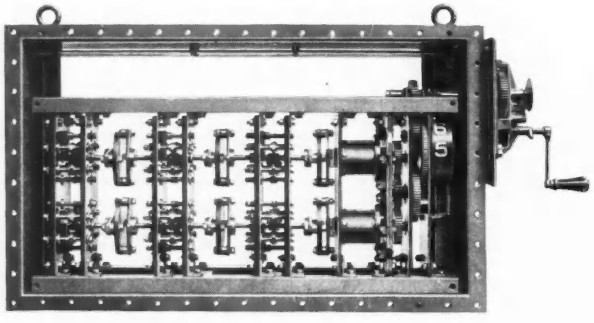


Fig. 19.—300 kVA transformer tap changer operated by a spring.

through the other half of the choke and switch S'_1. Switch S_2 is then closed, and the current again divides equally through the two halves of the auto-transformer. The winding ratio has now been altered to the extent of half the number of turns between the tapping section X and Y, and the tap change step is completed. Similarly, to reduce the number of turns of the winding still further, switch S'_1 is opened and S'_2 then closed. Further operations are carried out in a similar manner in order to increase or reduce the number of turns in the winding and alter the ratio of transformation. Fig. 19 shows a tap changer designed for the operation described.

On large transformers with numerous tapping steps, it is not economical to provide a large number of switches S suitable for breaking current. It is possible, however, to reduce the number to two by means of the circuit shown in fig. 17. These two switches are called diverter switches and are placed in the positions marked D and D'. The switches marked S_1 etc., which do not have to break current, are called selector switches.

The general principle of the tap change cycle is the same. To change the ratio one step, D is opened, and then S_1; S_2 is then closed, followed by the closing of D. To reduce the turns still more D' is opened, then S'_1. S'_2 is then closed and is followed by the closing of D'. In a similar manner the number of turns of the winding can be increased in steps. It will be noticed that the selectors never break current but only select the required tapping. Figs. 20 and 21 show tap changers using this system of diverter and selector switches.

It will be appreciated that the diverter switches D (fig. 17) are required to rupture the kVA difference during the movement from one step position to another. The oscillogram illustrated in fig. 25 shows a test on one of the contactor diverters in the tap changer shown in fig. 22, while fig. 23 shows the contactor. The kVA ruptured is more than five times that required when working at the maximum rating of the tap changer. On this test the arc was ruptured in just over three-quarters of a cycle.

Preventive Auto-transformers.

The number of ratios obtainable from the tapping points on the transformer winding is given by the expression $2n - 1$, where n is the number of winding tapping points. The doubling effect is made possible by the preventive auto-transformer. During normal working conditions when each half of the preventive auto-transformer carries an equal current, no reactive drop takes place as the ampere-turns of the two halves of the winding are in opposition. During the tap change operation, however, a condition arises in which the whole current flows through one half of the winding and a reactive drop occurs. This transient voltage drop produces a slight momentary displacement of the phase winding

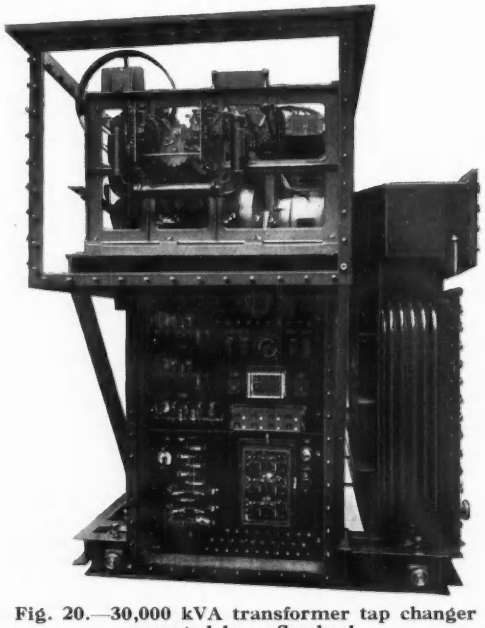


Fig. 20.—30,000 kVA transformer tap changer operated by a flywheel.

voltage vector, but with a correctly designed auto-transformer the effect can be reduced to a point where only a negligible disturbance is obtained on the transmission system.

Operating Requirements of Tap Changers.

When tap changers were in their infancy, only a few years ago, the danger of an auxiliary supply failure to the tap changer motor was perhaps unduly stressed, and it became the vogue to specify that once the tap change cycle began, it should be completed irrespective of the continuity of the auxiliary supply. This requirement necessitated the storing of sufficient

mechanical energy to effect the tap change before the tap change motion started. Figs. 19, 20 and 21 show tap changers in which this principle is embodied. The tap changer in fig. 20 uses the kinetic energy of a fly-wheel; that shown in fig. 21 employs the potential energy of a falling weight, while that in fig. 19 uses a spring.

In all such instances it is essential that the stored energy shall exceed by an ample margin the amount actually required by the tap change motion, so that should the mechanism become stiff in operation the tap change would still be completed at the desired speed. One of the disadvantages from the designer's point of view of the stored energy method of operation is the necessity for providing a brake, or stop, to absorb the excess energy after completion of the tap change.

Experience has shown that the result of an auxiliary supply failure is not so serious as anticipated provided that the preventive auto-transformer in the circuit shown in figs. 16 and 17 is designed so that each half of the winding is capable of carrying the whole current continuously. Even if the supply should fail, the chance is very remote of a major electrical failure caused by the mechanism stopping at just that part of the electrical cycle where either switch D or D' (fig. 17) is just opened sufficiently to cause continuous arcing.

There are many tap changers in operation which are directly coupled to the driving motor and no case of failure due to the hazard in question has been reported. Fig. 22 shows a directly driven tap changer, while fig. 24 shows the operating mechanism in detail. It is desirable, however, with a direct drive mechanism, to arrange that the transformer is switched off the line as soon as possible in the unlikely event of a tap change being uncompleted.

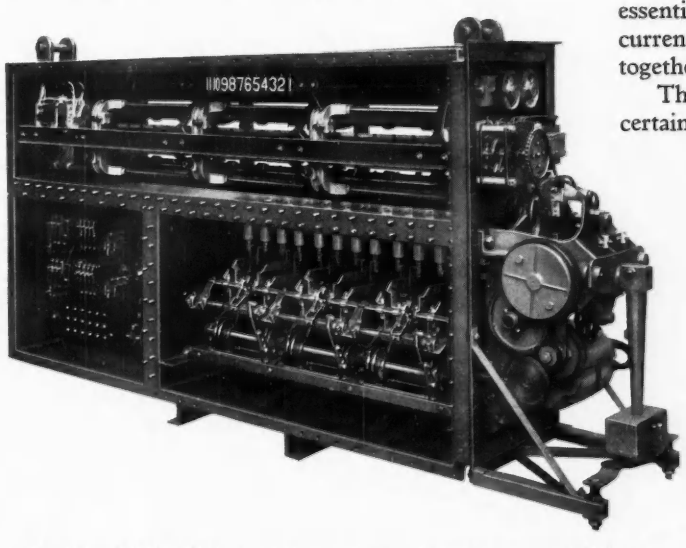


Fig. 21.—7,500 kVA transformer tap changer operated by a falling weight.

In the case of large transformers, remote indication of the tap change is usually given at the control station, and in the event of an uncompleted tap change the station engineer is able to transfer the load to another source and shut down the faulty equipment in the shortest possible time. With small

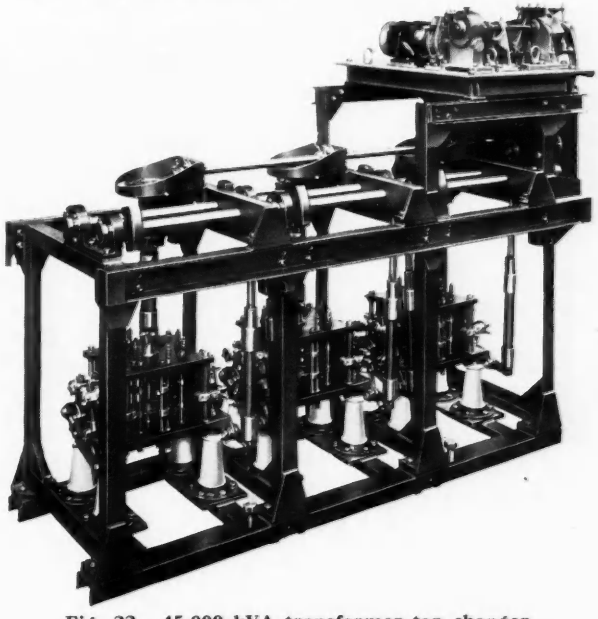


Fig. 22.—45,000 kVA transformer tap changer operated by direct motor drive.

distribution transformers, remote indicating apparatus is not likely to be installed, in which case it is probably better to trip the transformer out of circuit automatically should the mechanical cycle not be completed.

Mounting of Tap Changer on Transformer.

The tap changer circuit shown in fig. 17 requires essentially a number of switches D which break current, and a number of switches S which do not, together with the operating mechanism.

The functioning of the switches D produces a certain amount of carbon which is deposited in the oil in which the switches are immersed. This oil should therefore be completely isolated from the oil in the main transformer tank. The switches S, however, which do not break current, may be mounted on the transformer structure in the main tank thereby reducing manufacturing costs, but the modern tendency is to incorporate both switches D and S in an easily detachable tank mounted externally on the transformer tank. This method not only facilitates inspection, maintenance and repairs, but also, should a failure of the selectors take place, avoids pollution of the oil in the main tank and minimizes the danger of the transformer itself

becoming involved in the breakdown. Further, the complete faulty tap changer can be detached from the transformer tank and a spare one installed, or alternatively, temporary working arranged without the tap changer by continuing on a fixed tapping.

A handle is normally supplied for making a tap change in case of emergency. It is desirable in this connection that the tap changer is mounted on the transformer so that the necessary clearance required by Home Office regulations is obtained between the operator and the nearest live metal. Alternatively, a protective guard should be provided. Fig. 7 in Part I. of this article shows a tap changer mounted on the transformer at ground level to give the required clearance.

Electric Control of Tap Changing Gear.

Tap changers may be designed for operation :—

(a) By hand.

(b) By local and/or remote push button control.

(c) Automatically.

Few operating conditions arise in which hand operation alone is sufficient, but in these instances the tap changing equipment is naturally much cheaper than with push button or automatic operation, especially in the case of small and medium size transformers as shown in Part I. of this article.

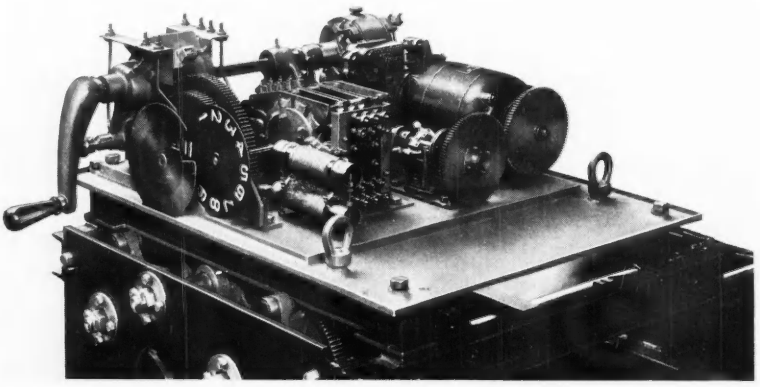
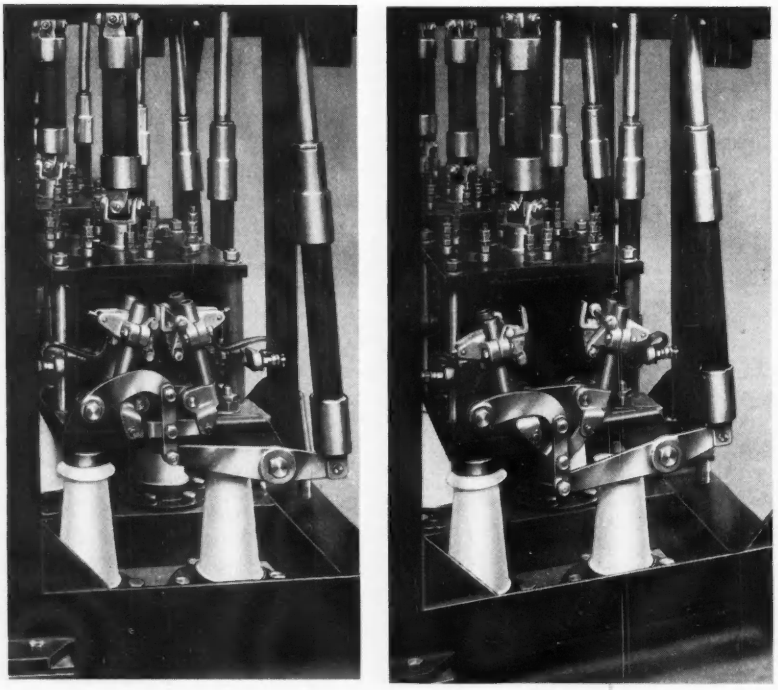


Fig. 24.—Detail view of motor operating mechanism for the tap changer in fig. 22.

Remote push button operation is usually under the control of the station engineer and is in general use at all stations, such as S_1 to S_9, fig. 9[1], where the power flow is controlled to and from the transmission system. When stations such as S_9 cease to generate, automatic operation will probably be installed in order to maintain a constant voltage or rising voltage-load characteristic on the bulk supply busbars *B*.

When remote or automatic control is used, local push button control on the tap changer is incorporated for test purposes, in addition to the emergency hand operation control. For automatic operation the tap change movement is initiated by a voltage regulating relay, described later.

In all instances of automatic operation it is necessary to consider whether it is desirable to aim at keeping the voltage constant on the outgoing side of the transformer or whether compounding is required, *i.e.*, a rising voltage characteristic with load. By means of compounding, the voltage at a point remote from the transformer can be kept at approximately a constant value. If compounding is desirable, it is necessary to decide whether compensation is required for the

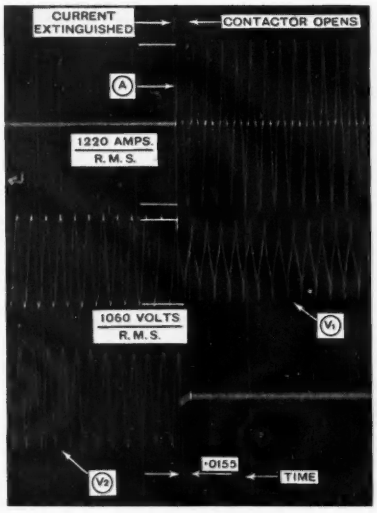


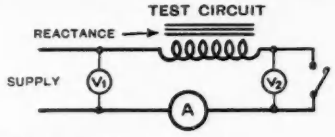
(a) (b)

Fig. 23.—Operating contactor for the tap changer shown in fig. 22 (a) closed (b) open.

1 This illustration appeared in Part I. of this Article (G.E.C. Journal, Vol. VI. No. 3, p. 138) and is reproduced on page 154.

resistance drop of cables only, or for the reactance drop of transformers further along the system, or both. In order to provide the compounding feature, the control gear must include a compensator which is virtually a small scale model of that part of the line for which compensation is required. The compensator reduces, with increase in load, the voltage obtained from the secondary of the transformer which actuates the voltage regulating relay.





A —Current in contactor.
V_1—Supply voltage.
V_2—Voltage across contactor contacts.

Fig. 25.—Oscillogram of a test on diverter switch for tap changer shown in fig. 22. Top—current through diverter switch; middle—voltage across tapping section; bottom—voltage across diverter switch.

Relays for Automatic Voltage Regulation.

The voltage regulating relay, fig. 26, may, for example, be inserted on the secondary side of the transformer at station S_7 in the electrical circuit shown in fig. 9, for the purpose of maintaining a constant supply voltage, or alternatively, for giving a rising voltage-load characteristic to the system. Under normal conditions the beam of the voltage regulating relay floats, but with a variation in supply voltage the beam makes one of two contacts A, fig. 28, depending on whether the voltage is high or low, and a circuit is completed through a time delay relay, fig. 27, *via* contacts B. After a predetermined time the contacts of the time delay relay B break, and make those of C with a snap action, thus completing the contactor circuit which operates the tap change motor in the appropriate direction for raising or lowering the voltage. The change over from contacts B to contacts C breaks the time delay relay coil circuit and the relay returns to its off position, breaking the C contacts after a slight time delay, and later remaking B contacts. In the meantime the tap changer has operated and the voltage corrected before the B contacts are made, thus returning the voltage regulating relay beam to the midway position unless the circuit voltage condition is such that it is still necessary to make further correction. Limit switches LS are incorporated in the circuit to prevent further tap changes taking place when the tap changer is at the end of its travel towards the maximum or minimum voltage ratio condition.

The voltage regulating relay can be set to maintain the system voltage within plus and minus 1.0 per cent of normal.

BOOSTERS FOR TRANSMISSION AND FEEDER SYSTEMS.

In those cases where transformers without tap changers are already installed on a system and where no provision for installing tap changers at a later date has been made, voltage correction can be carried out by means of boosters, the application of which does not alter the phase angle of the system. Figs. 29 and 30 show two common circuit connections, single phase systems being taken for the sake of simplicity. The simple circuit fig. 29 is essentially suitable for small boosters on 440 volt distributors at such positions as Q, fig. 9. It will be noted that the tap change switch must be designed for the system voltage.

Fig. 30 is a useful circuit, of which many modifications exist whereby a standard switch designed for any voltage can be used for regulating any voltage feeder. The regulating transformer takes its supply from the feeder and transforms it

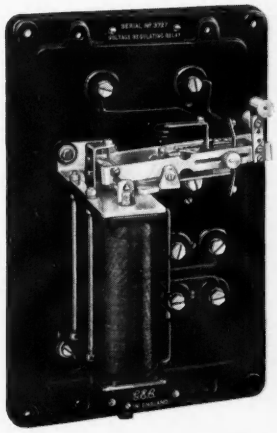


Fig. 26.—Voltage regulating relay for the automatic control of tap changers.

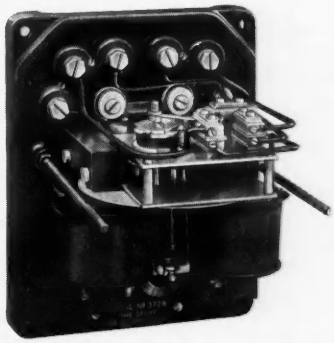


Fig. 27.—Time delay relay for the automatic control of tap changers.

down to a tapped secondary winding, the voltage of which is made to suit the standard switch. The voltage which is obtained from the tapped secondary by means of the on-load switch is adjustable in steps, and is applied to the primary of the boosting transformer which is wound for the correct ratio to give the required voltage regulation.

This circuit is frequently found to be the most economical, not only on 33 kV feeders where an 11 kV switch may be employed, but also at such a position as A, fig. 9 on an 11 kV feeder, where a 440 volt air insulated on-load switch of low cost can be used.

The tap changers and control gear for boosters are similar to those used on transformer tap changers.

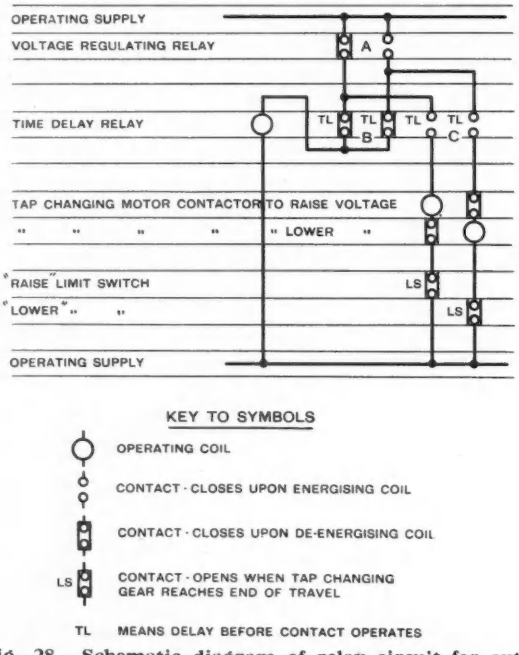


Fig. 28.—Schematic diagram of relay circuit for automatic voltage control of tap changer.

SELF-COMPOUNDING VOLTAGE REGULATORS.

Suitable tap changing gear for installation on feeder substation transformers (S, fig. 9) has already been described. Such tap changers, however, become economically unsatisfactory in most cases for transformers of 200 kVA capacity and below.

An interesting and useful solution of this problem, although of limited application, is found in the use of self-compounding voltage regulators, which can be made suitable for small transformers connected to H.V. feeders at such positions as T_3 fig. 9, or in the form of boosters on the 440 volt 4-wire distributors at such positions as Q, fig. 9.

When considering the application of these regulators the following points should be borne in mind:—

(a) The voltage drop to be corrected must be due solely to that current which passes through the regulator. For example, a regulator installed at either T_3 or Q would correct the voltage due to the voltage drop in the distributor but would not correct the voltage due to a drop in the H.V. feeders.

(b) The regulated distributor must not be paralleled with another distributor fed from a different source, as there is a phase displacement ϕ of the regulated voltage, fig. 31.

(c) The load current to be supplied by the regulator must be at, or approximately near, unity power factor. Maximum boost is obtained at unity power factor. At a reduced value of power factor the boost obtained decreases and becomes practically nothing at a load power factor of .94.

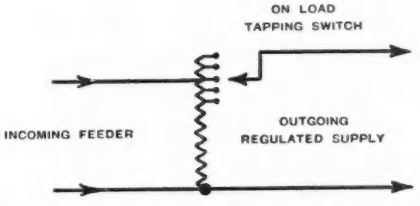


Fig. 29.—Single phase diagram of connections for small boosters with on load tap changers.

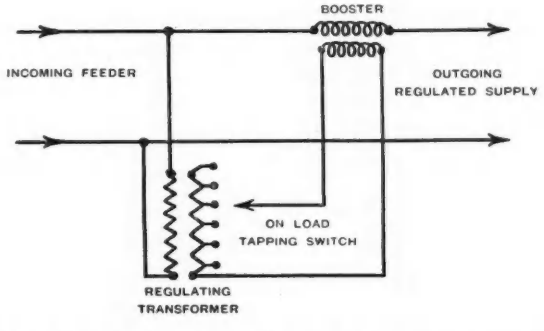


Fig. 30.—Single phase diagram of connections for boosters with on load tap changers.

(d) Commercial considerations limit the design to a maximum boost between no load and full load of 7 per cent at unity power factor.

(e) The regulator is suitable for three phase four wire distributors with unbalanced loading.

(f) The regulator can be designed to increase either the output voltage with a maintained voltage at its primary terminals, or maintain constant output voltage with a varying input voltage providing such variation in voltage is directly proportional to the load taken by the regulator.

Design Theory of Self-compounding Regulators.

Fig. 31 shows a diagram of a self-compounding, single phase booster. The general circuit conditions, however, apply equally well to three phase boosters or double wound transformers. It will be seen that the circuit consists essentially of a choke and a

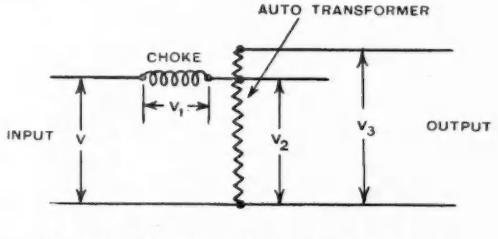
transformer primary winding in series, across which is applied the incoming voltage V.

Due to the magnetizing current I_m taken by the transformer, reactive voltage V_1 will appear across the choke and V_2 across the primary of the auto-transformer, the sum of these being equal to the applied voltage V.

If a load current I_L is taken from the output side of the booster, the current through the choke will be the vector sum of $I_m + I_L = I_T$, and the voltage of the choke will now assume a new position V'_1 as the voltage across it will be approximately 90° out of phase with the total current I_T. Now the choke is so designed that on no load, when magnetizing current only is flowing, saturation of the core takes place, and hence the total current I_T through the choke will not increase the magnitude of the voltage across it. Thus, the magnitude of the output voltage V'_2 must be greater than V_2.

The secondary winding of the auto-transformer is designed to step up the voltage in order to compensate for the voltage drop across the choke under the no load conditions; hence on no load $V_3 = V$.

The choke and transformer are mounted in the same tank to form a single unit, as shown in fig. 32.



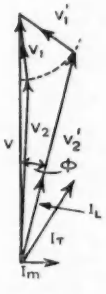


Fig. 31.—Circuit and vector diagrams of a self-compounding single phase booster.

STATIC BALANCERS FOR VOLTAGE REGULATION OF DISTRIBUTORS.

The copper section of low voltage distributors is usually governed by the limitation of voltage drop and not by thermal considerations. Due to the growth of domestic loads such as cookers, radiators and water heaters, which are usually connected between the outer and neutral of a 4-wire system, the out-of-balance loading has of recent years increased. The out of balance current which flows in the neutral of a 4-wire system produces a voltage drop therein, which reduces the voltage across the heavily loaded phase and increases the voltage to neutral of the lighter loaded phases. This effect may be minimized by introducing a static balancer comprising a simple 1/1 ratio auto-transformer which, for three phase working, is connected inter-star as shown in figs. 33 and 34.

When connected to the three phase 3-wire system, fig. 33, to form an artificial neutral, the balancer will divide the phase to neutral load current x into three equal parts, thus reducing the current in the loaded line by one third, and reducing its voltage drop. This system can be used with

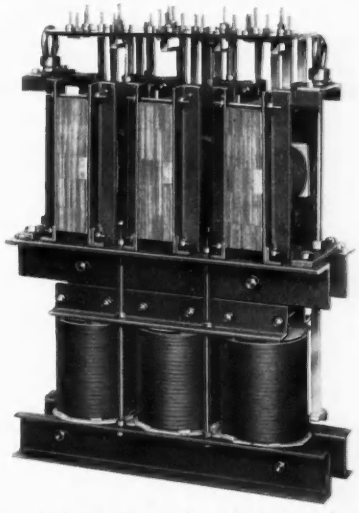


Fig. 32.—Automatic static voltage regulator for low voltage feeders.

advantage on a 400 volt, 3-wire distributor, to provide a neutral point for 230 volt lighting or other purpose, or to balance a large single unbalanced load on an otherwise well balanced four wire system. In the latter case the supply neutral would not be connected to the balancer neutral.

The most normal case in practice is the installation of a balancer on a four wire distributor in which the earthed neutral wire, usually of the same cross sectional area as the outers, is connected to the neutral point of the balancer as shown in fig. 34.

A balancer installed on such a system will not divert the whole of the out-of-balance current into the three outers, the current diverted being proportional to the inverse ratio of the impedances of the direct path for the current, *via* the line, load and neutral, to the second path, line, load, balancer neutral point and balancer.

It will be seen, therefore, that for efficient balancing the impedance of the balancer must be kept low, and as the balancer must have some impedance, the system does not in general function as efficiently as when the supply neutral is disconnected. It is sometimes recommended that the neutral should be disconnected, or cut, at Z, which in effect produces a 3-wire system as shown in fig. 33. This arrangement has the disadvantage that an out-of-balance load on one phase of the supply side of the cut cannot be balanced directly by a

deficiency of load on the same phase, but on the other side of the cut. With the cut neutral, the whole current is taken by the balancer which therefore functions more efficiently, but for the same voltage drop across the balancer it will be more costly.

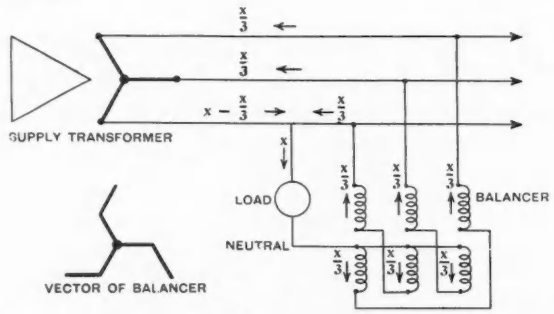


Fig. 33.—Balancer and artificial neutral for three phase 3-wire distributors, showing division of load current through balancer and lines.

A compromise may be made between the two systems of cut and uncut neutral by incorporating a choke in the supply neutral at the point Z, thus raising its impedance and diverting more current through the balancer. The inclusion of a choke is an added complication and its cost has to be taken into consideration. Further, if the choke is of a sufficiently high value to produce much better balancing, then under system fault conditions the advantage of the earthed neutral is lost. In the author's opinion, the best system is that of directly connecting the supply neutral to the balancer neutral.

As regards the position of the balancer, it should

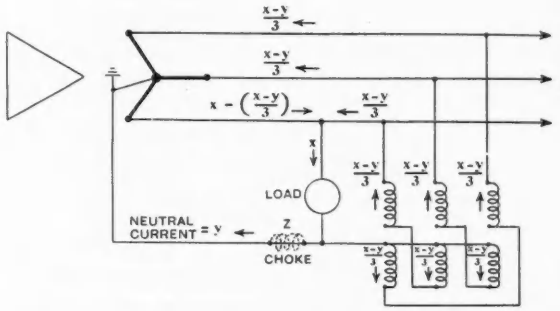


Fig. 34.—Balancer connected to a three phase, 4-wire distributor showing division of load current.

be so installed on the distributor that the out-of-balance loading occurs between it and the supply. The voltage drop due to an out-of-balance is greater when the out-of-balance occurs at a point beyond the balancer towards the tail end, than when it lies between the balancer and the source of supply. For normal systems it is therefore usual to install the balancer close to the tail end of the distributor.

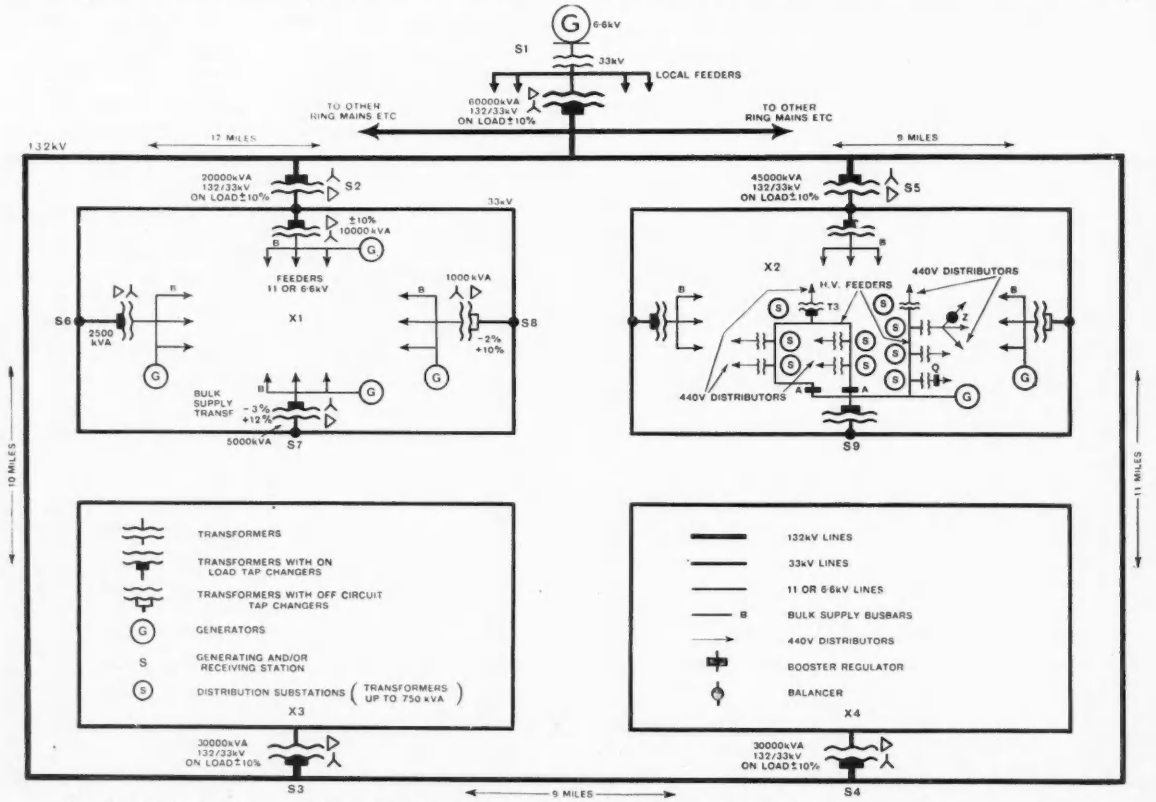


Fig. 9.—(*Reproduced from Part I., Vol. VI., No. 3.*)—Schematic transmission and distribution diagram showing positions at which regulating apparatus can be installed.